NINJA

INSTITUTE FOR ADVANCED RESEARCH
NAGOYA UNIVERSITY
SINCE 2002

NINJA Experiment :
Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

Tsutomu Fukuda (IAR/F-lab, Nagoya Univ., Japan)
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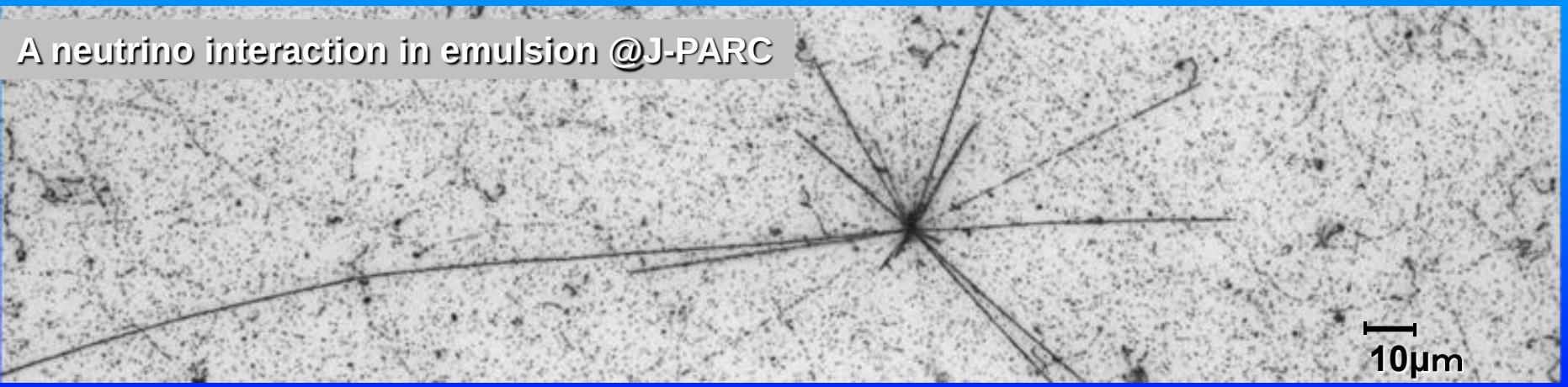


Fermilab Neutrino Seminar, 11th Jun. 2020

Introduction of presenter

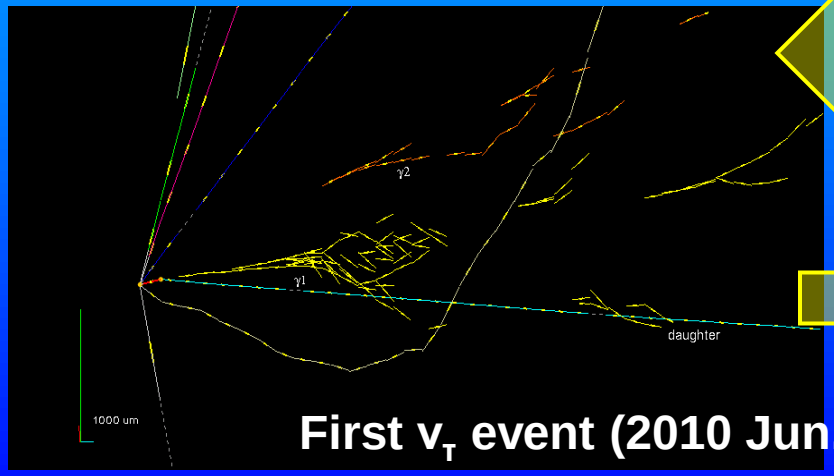
- Tsutomu Fukuda (福田　努)

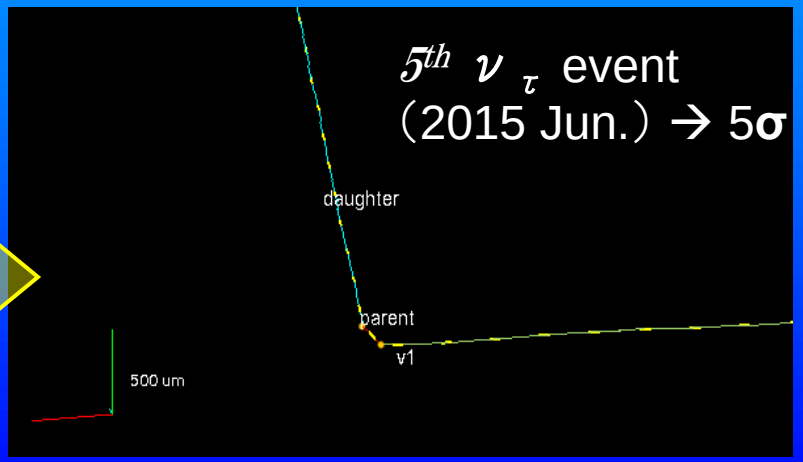
  Designated assistant professor in Nagoya University
  Fundamental particle physics laboratory (F-lab)
  Ph.D : Neutrino event detection in OPERA
  (Nagoya Univ., Mar. 2010)

- Research
  - OPERA experiment (2003 ~)
  - NINJA experiment (2014 ~)
  - Development of emulsion technology

Introduction of presenter

- My activity for particle physics from 2003.
  (emulsion film preparation for OPERA experiment)



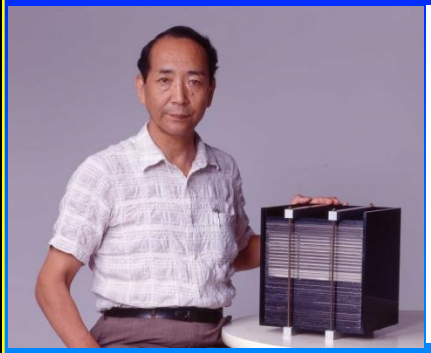


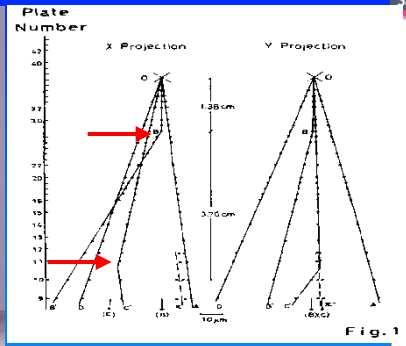
History of our emulsion laboratory

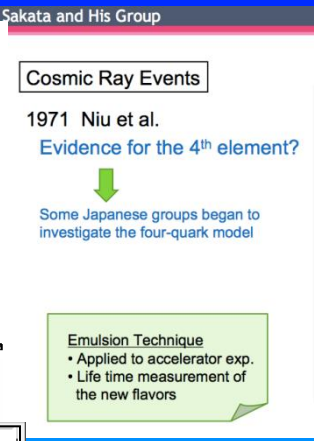
1896 (A.H.Becquerel)
Discovery of Radioactivity
1947 (C.Powell et al.)
Discovery of π

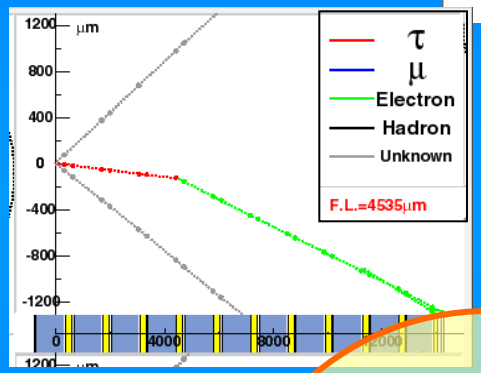
F-lab.

1971 (K.Niu et al.)
Discovery of charm particle in cosmic-ray
1986 (K.Niwa et al., E531)
*Indirect observation of ν_τ
2001 (K.Niwa et al., DONUT)
Direct observation of ν_τ
2015 (K.Niwa et al., OPERA)
Discovery of ν_τ appearance









Now

OPERA
2001-2019

NINJA
2015-

CHORUS
1990-2000

DONUT
1994-2005

SHiP
2026-

Fermilab E531
1978-1983

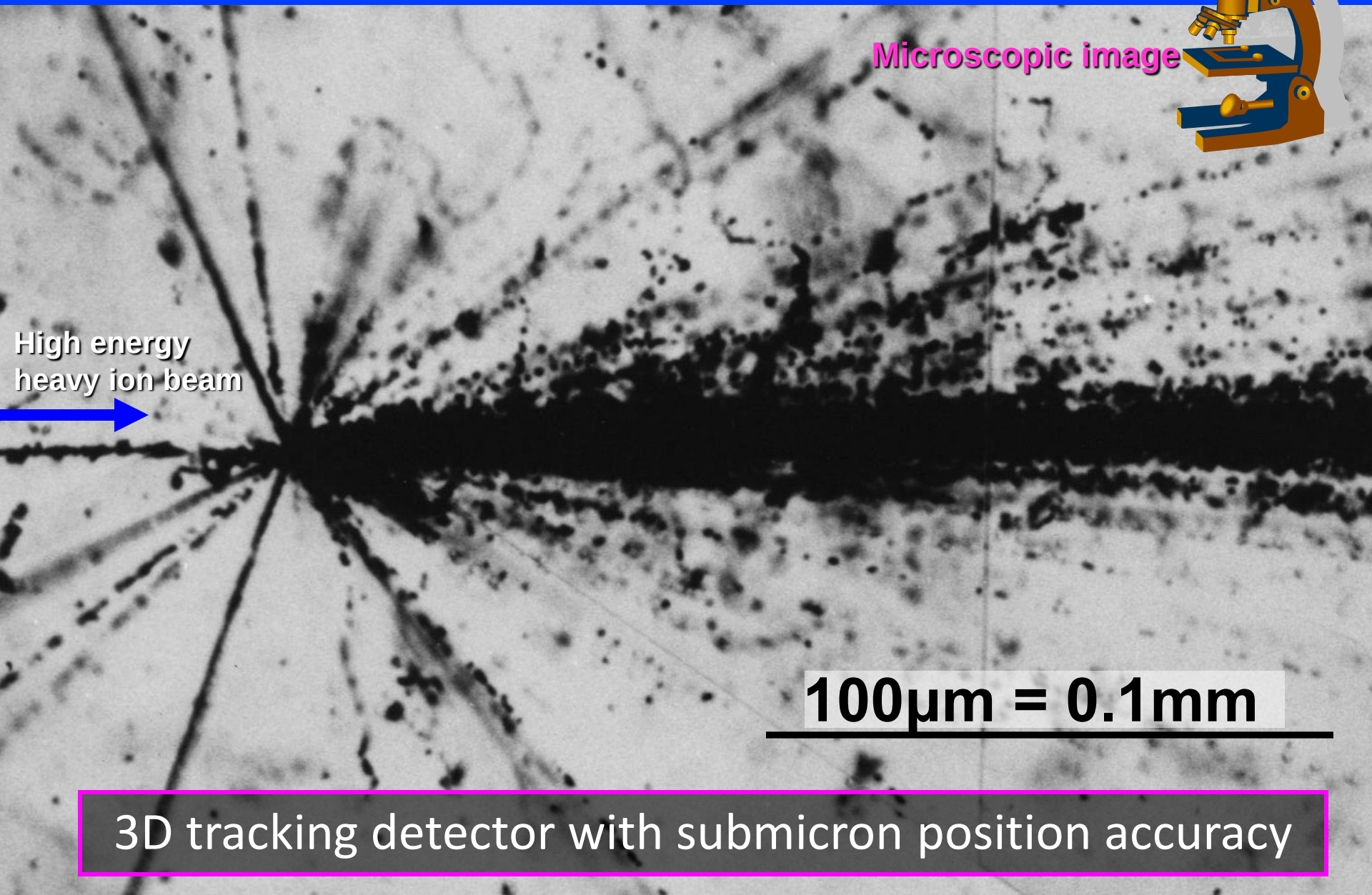
Neutrino experiment with Nuclear Emulsion in Nagoya Univ.

* see A.Blondel, arXiv:1812.11362v2,
G. Feldman's slide@Rencontres du Vietnam 2019

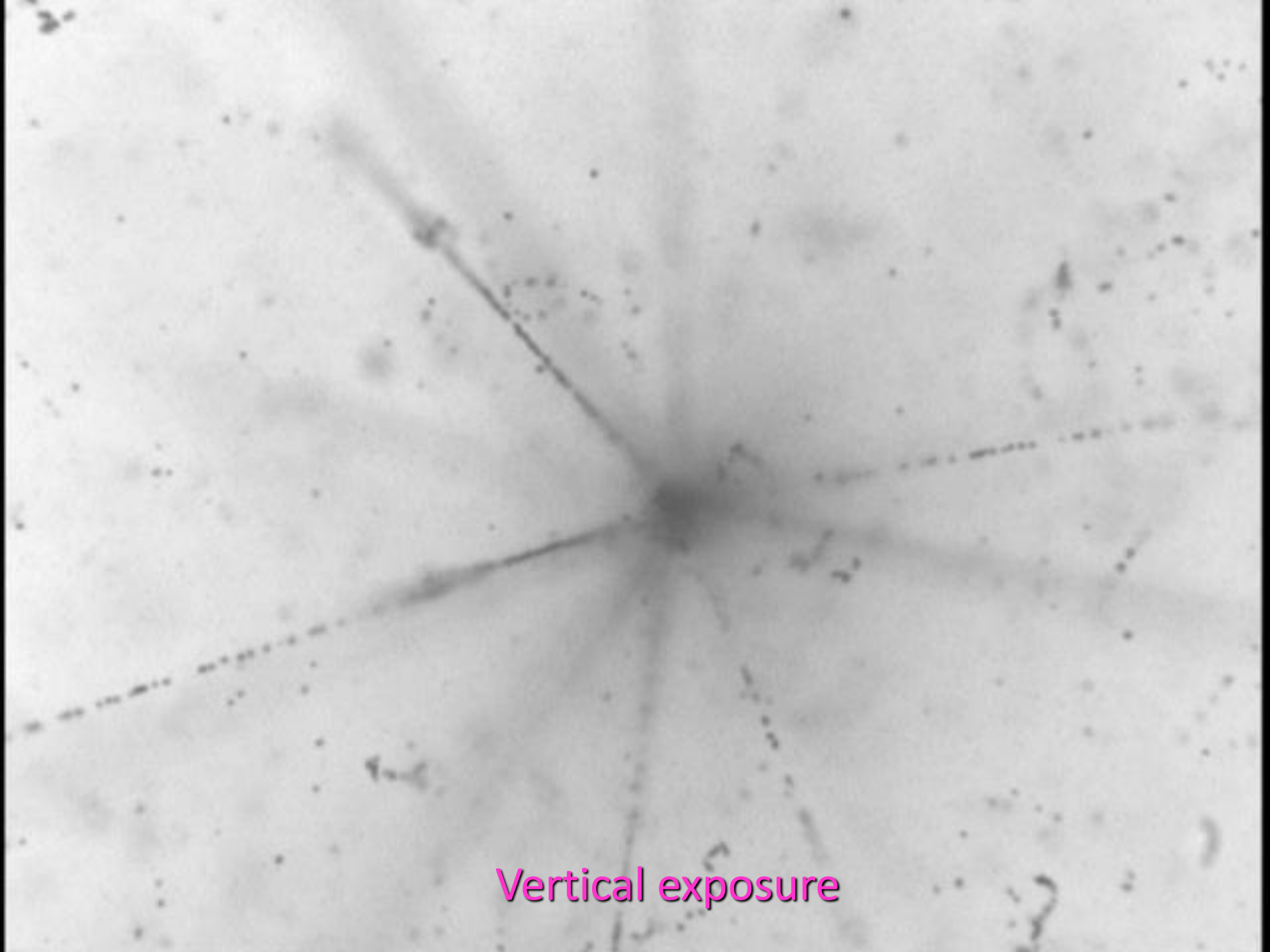
Contents

- Nuclear emulsion
- NINJA experiment

What is Nuclear Emulsion ?



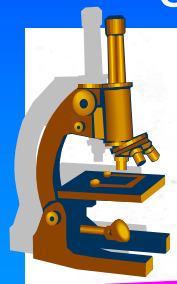
3D tracking detector with submicron position accuracy

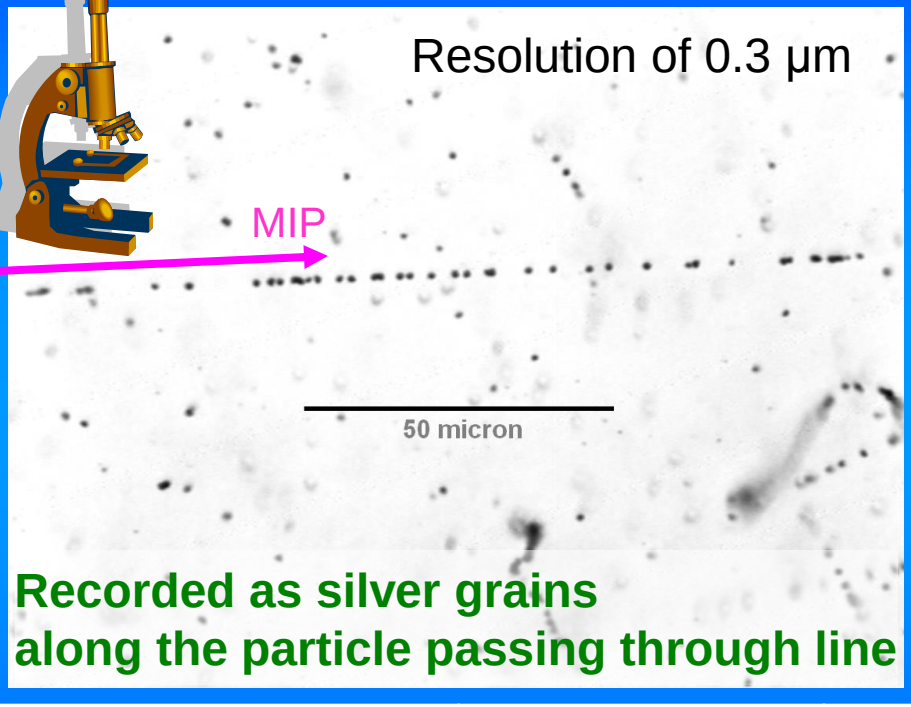


Vertical exposure

Photographic Film technology

- Nuclear Emulsion is a special photographic film.
- Signal is amplified by chemical process.





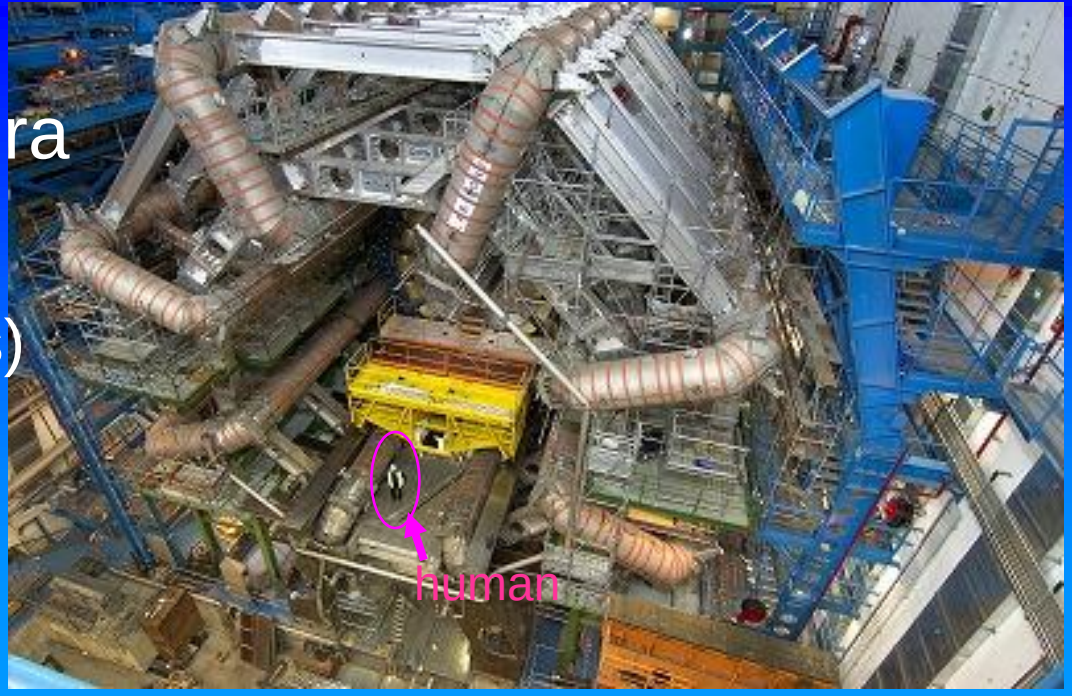
Recorded as silver grains along the particle passing through line

	Merit	Image detection
Film camera	**High resolution**	Sliver halide (Photochemical reaction)
Digital camera	Real time	CCD, CMOS (Photoelectric conversion)

Largest Digital Camera

ATLAS detector

(~1.6 x 10^8 image sensors)

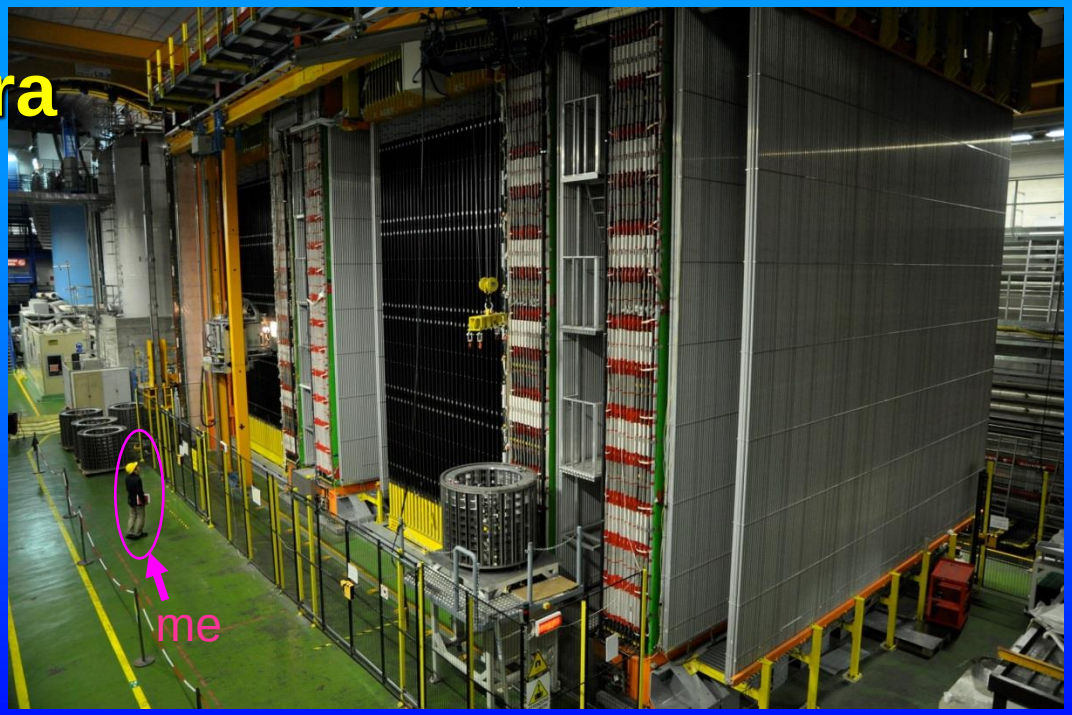


Largest Film Camera

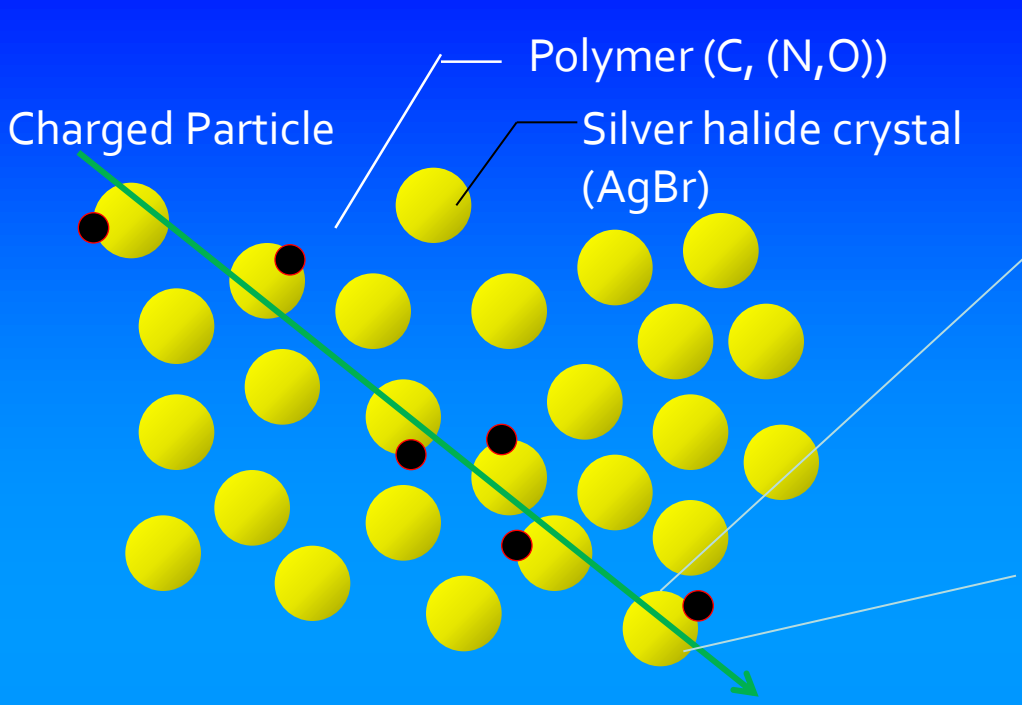
OPERA detector

(~10^{20} AgBr crystals)

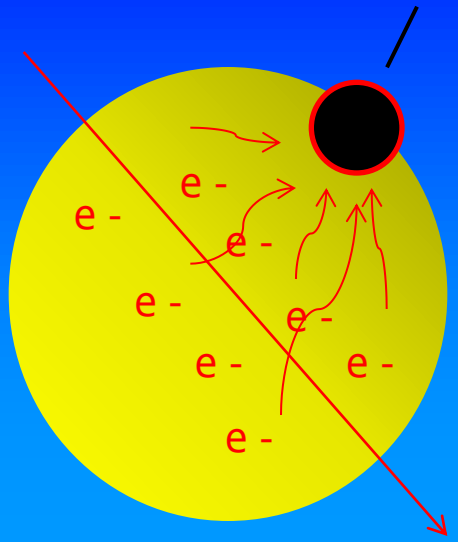
9000,000 emulsion films



Nuclear Emulsion Detector

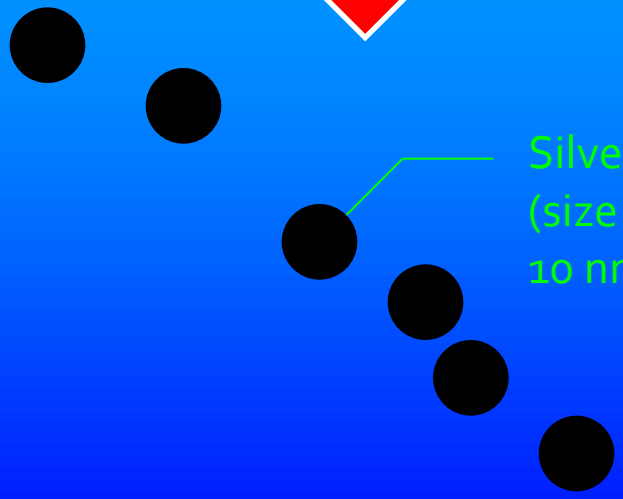


$Ag^{+} + e^{-} \rightarrow Ag_1 \cdot \cdot \cdot Ag_n$



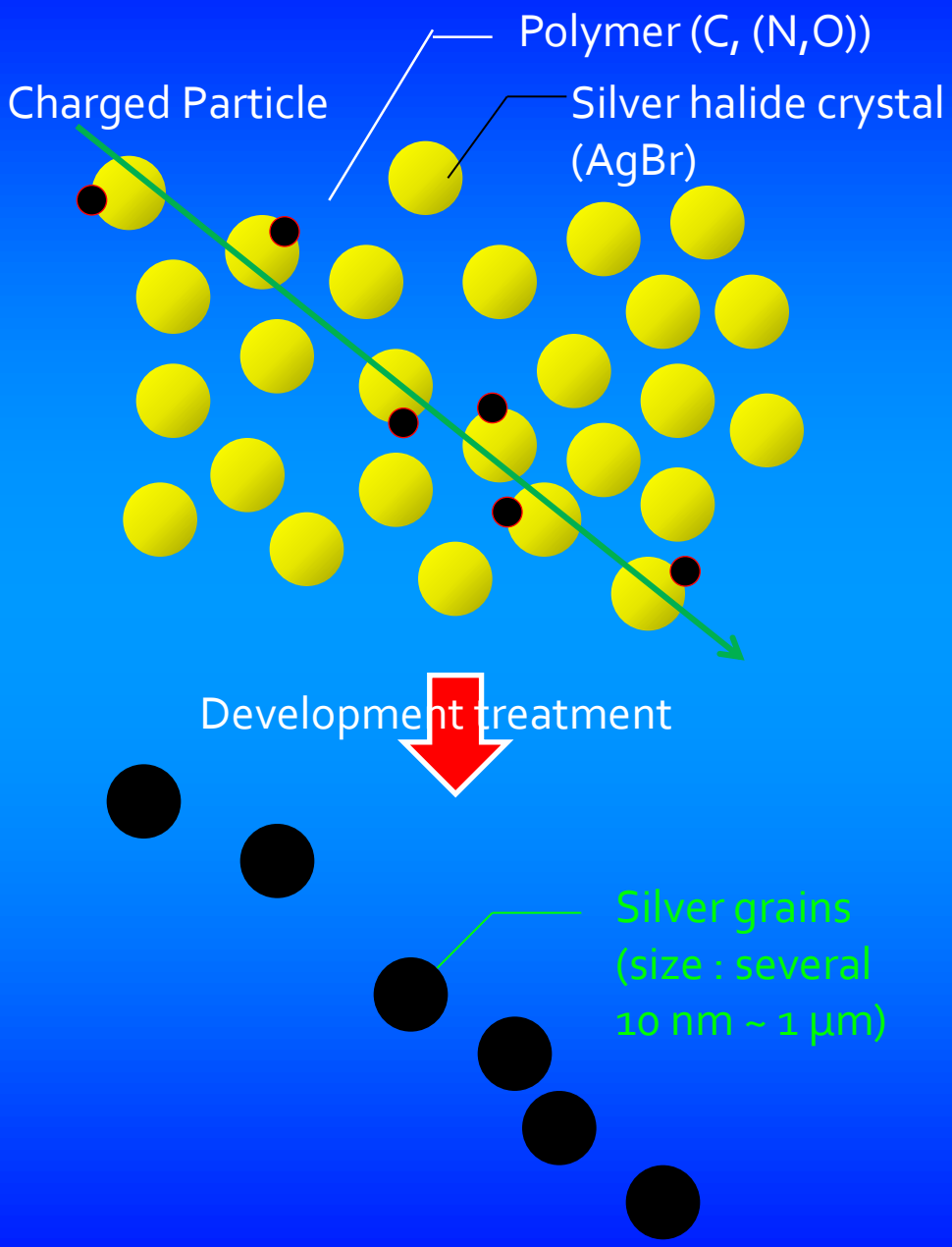
Ionized electrons concentrated on the electron trap to form the latent image specks in a crystal

Development treatment

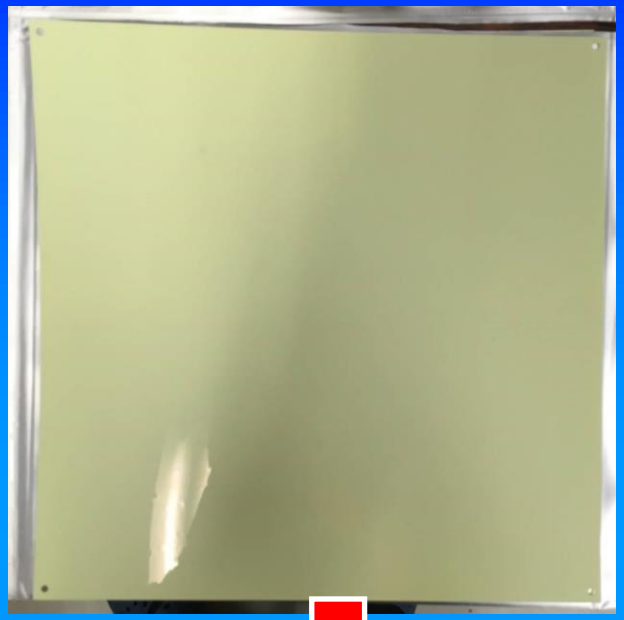


Silver grains
(size : several
10 nm ~ 1 μm)

Nuclear Emulsion Detector

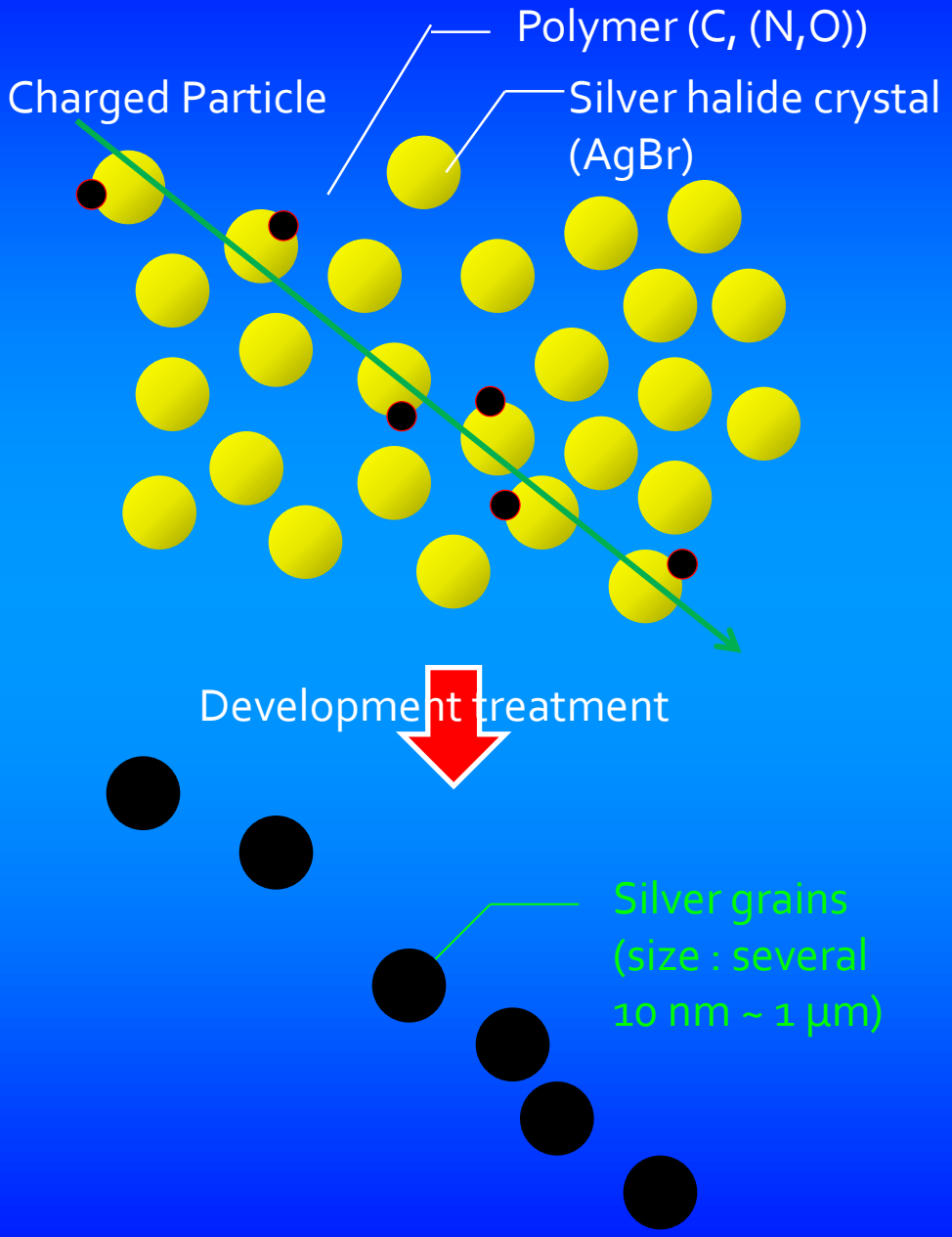


Emulsion film

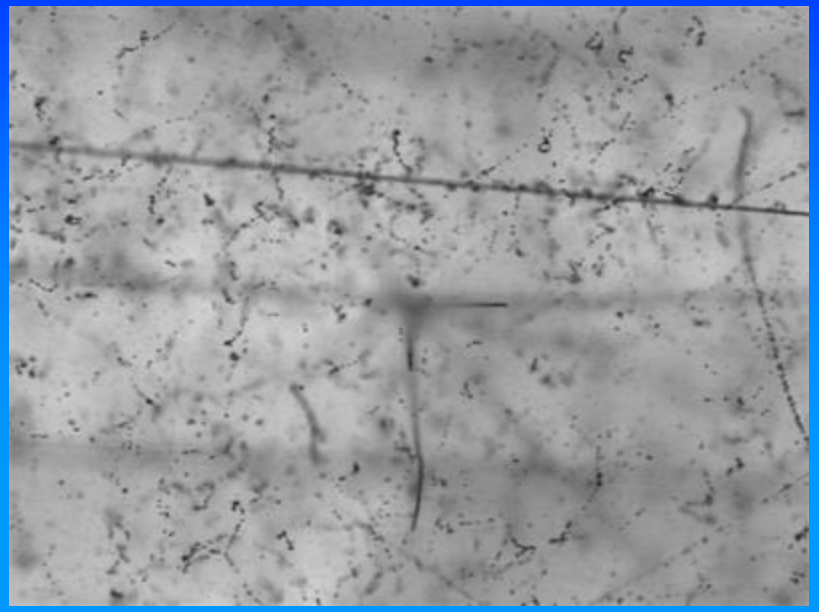


Development treatment

Nuclear Emulsion Detector



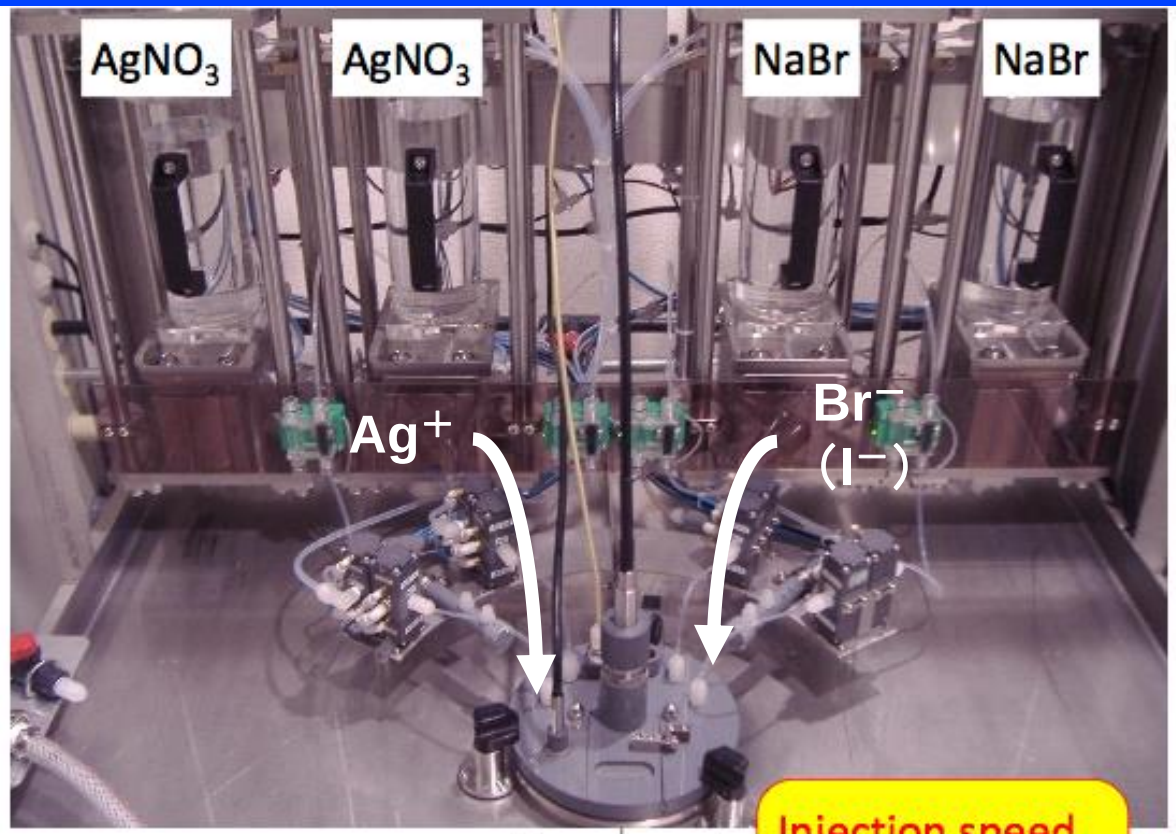
Nuclear spallation reaction by heavy ion



Spatial resolution
- silver halide crystal size
- number density of silver halide crystal

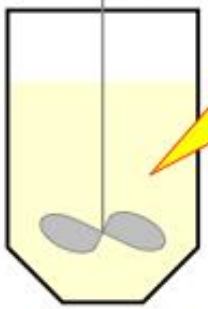
Sensitivity
- Chemical treatment
- Crystal defect and doping etc.

Production of emulsion gel



Chemical reaction

$AgNO_3 + NaBr \rightarrow AgBr\downarrow + NaNO_3$

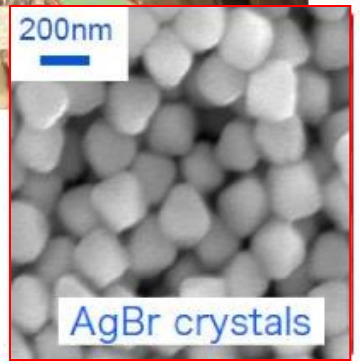


Injection speed
Mixing speed
Temperature

Crystal size
Crystal shape

chemical

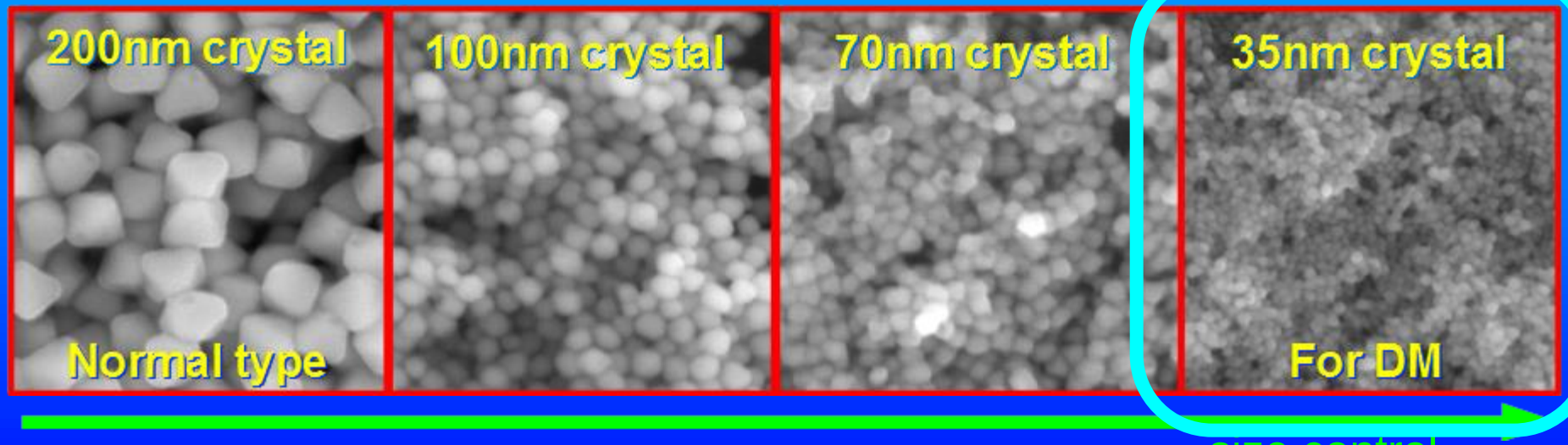
Sensitivity
Stability



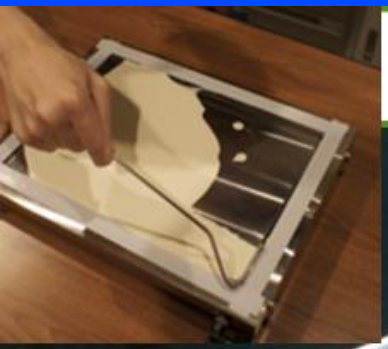
Chemical process

Production of emulsion gel

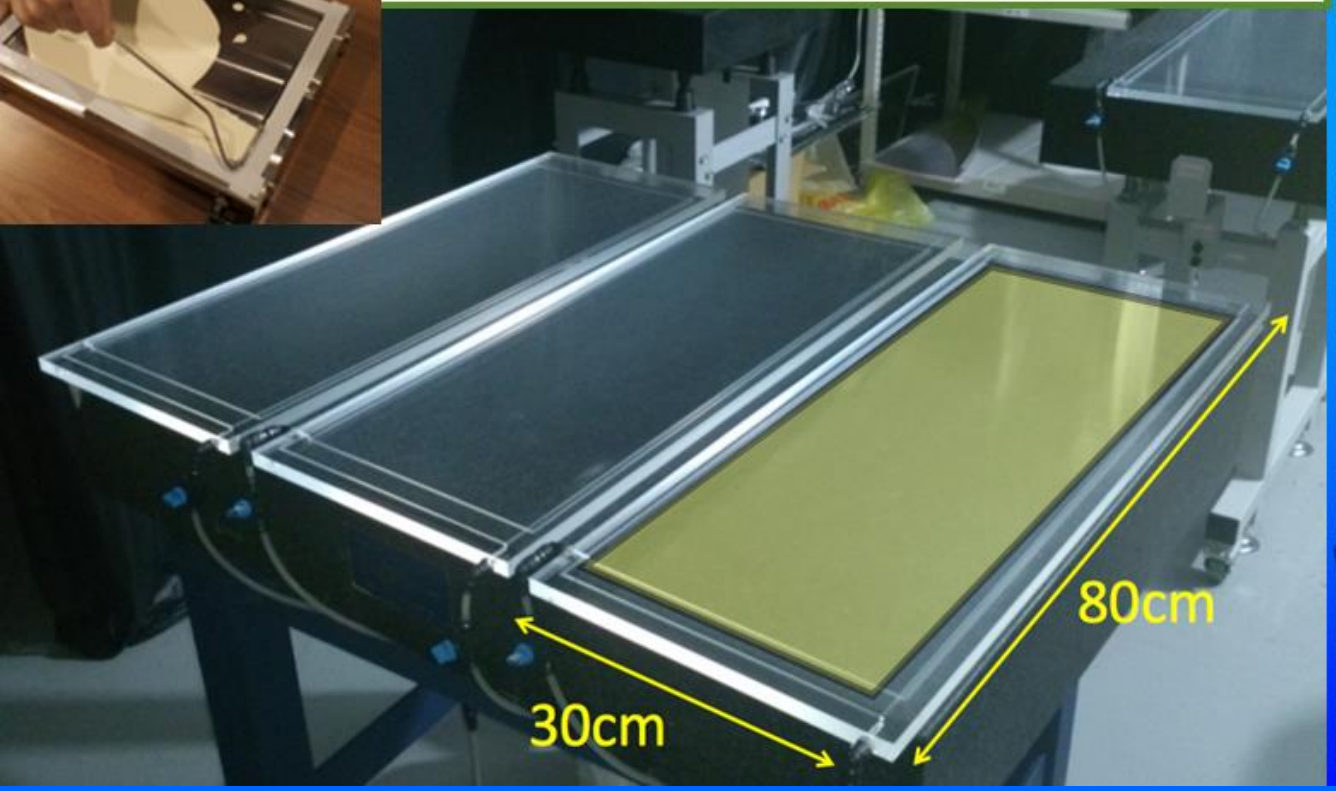
Nuclear emulsion gel is made by ourselves



Emulsion film production in the lab



Pouring: Temp.20℃, R.H. 80-90%

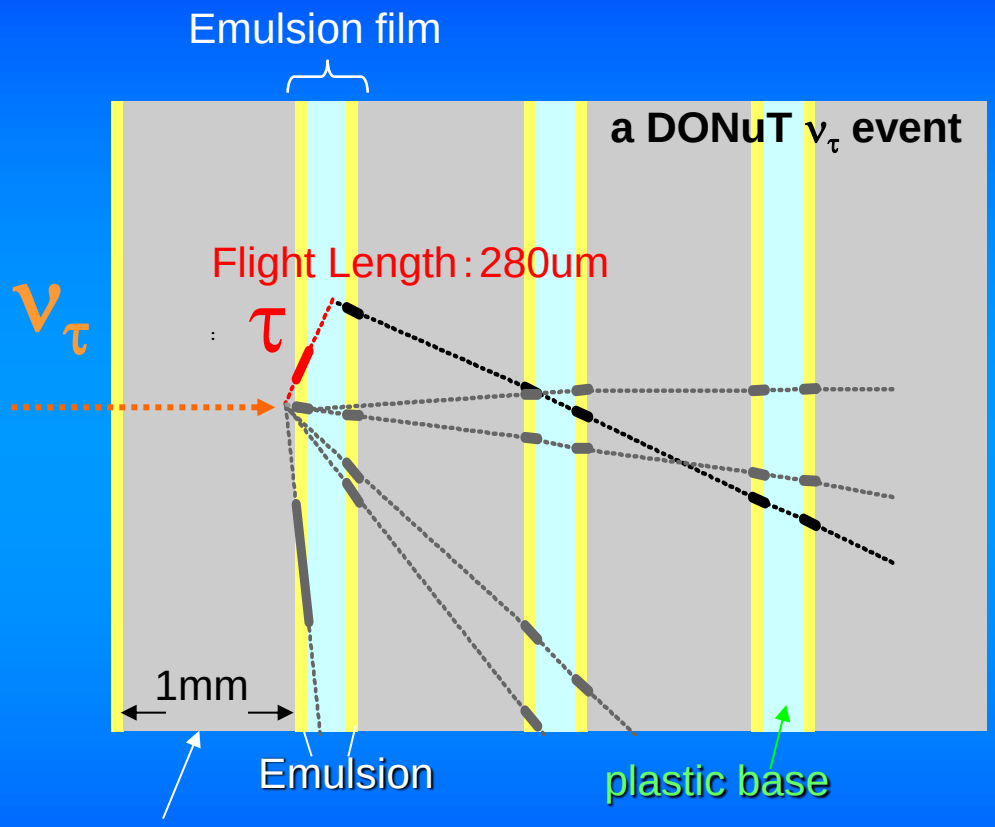


Drying: Temp. 30℃ R.H. 70-80%

Gel melting → Pouring → Drying

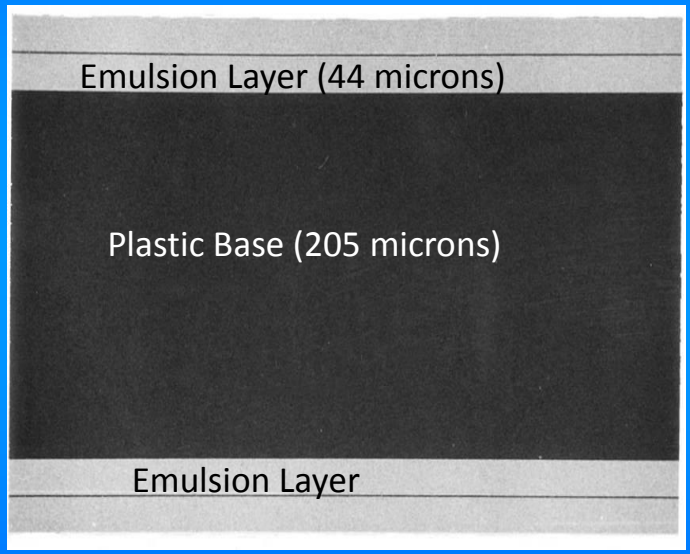
Currently an automatic pouring and drying system is developed.

Emulsion Cloud Chamber (ECC)



DONuT : Iron 1mm
OPERA : Lead 1mm
NINJA : Iron 0.5mm, Water 2.3mm

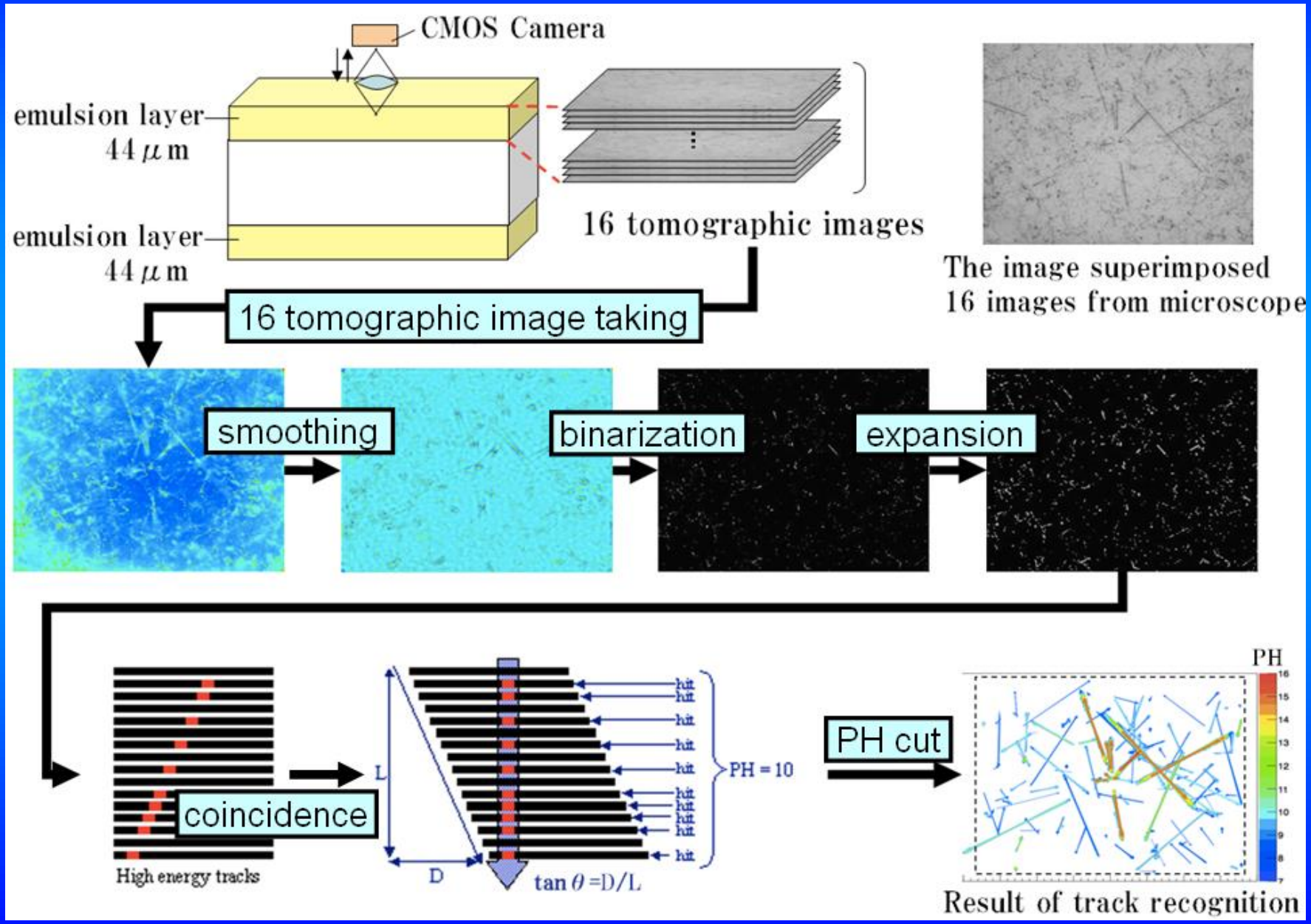
basic detector: AgBr crystal,
size = 0.2 micron
detection eff.= 0.16/crystal
10^{13} "detectors" per film



44-70μm emulsion gel were coated on both sides of the ~200μm-thick plastic base.

Sandwich structure of emulsion films and target material.

Automatic track recognition



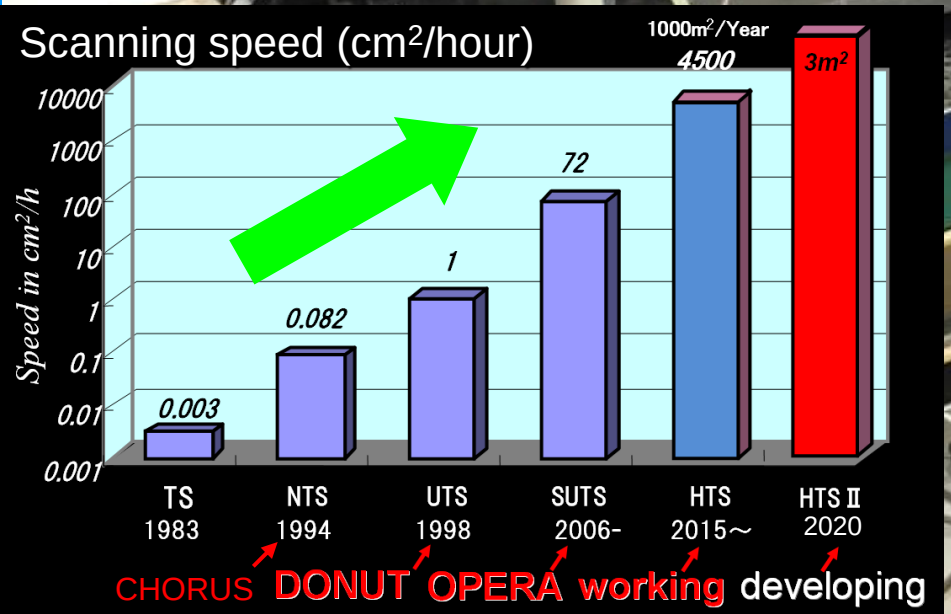
Hyper Track Selector

Camera:
2MP 72 sensors

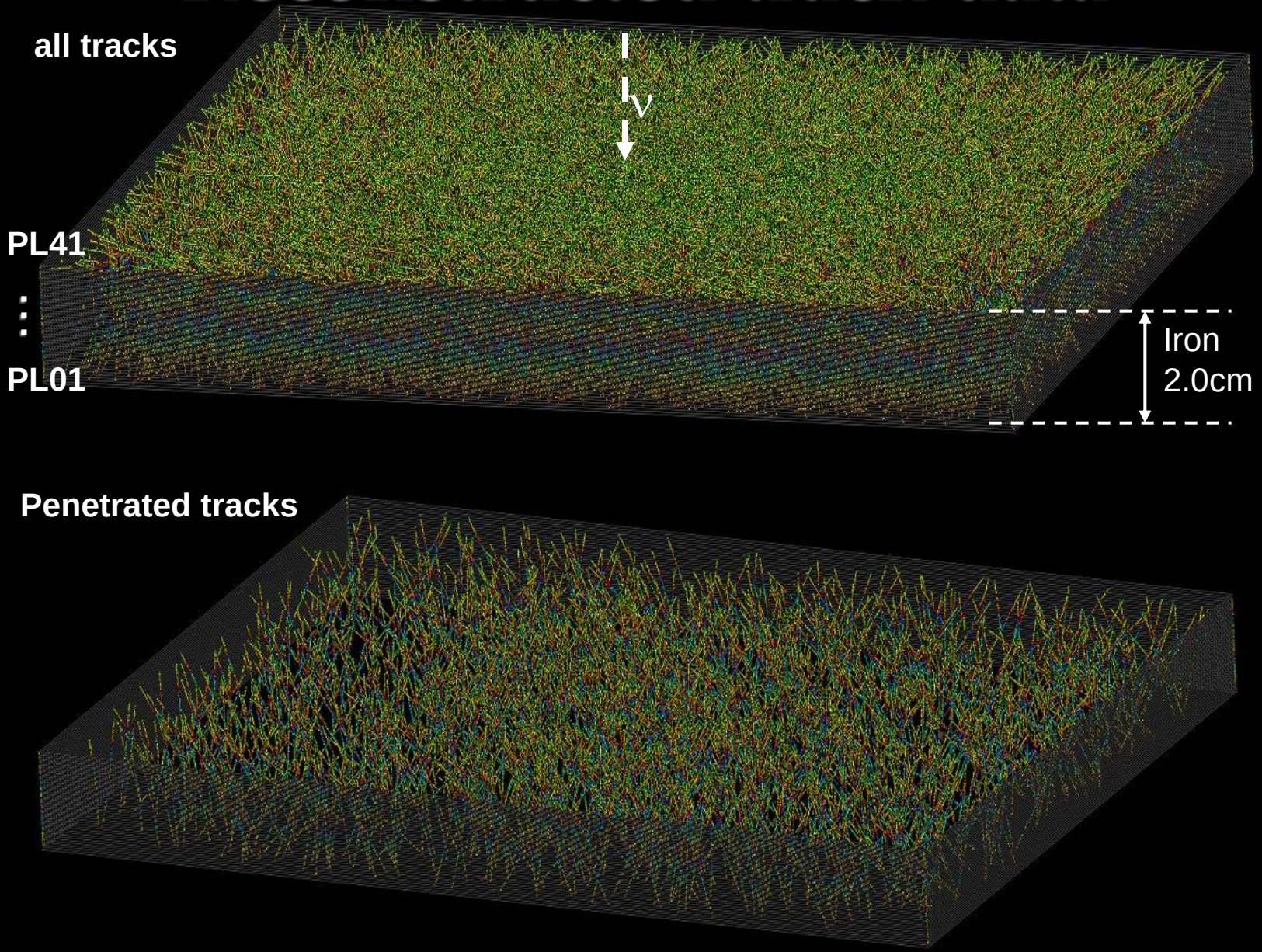
Image processing:
72 GPUs in 36 PCs

Lenz:
FOV 25mm^2

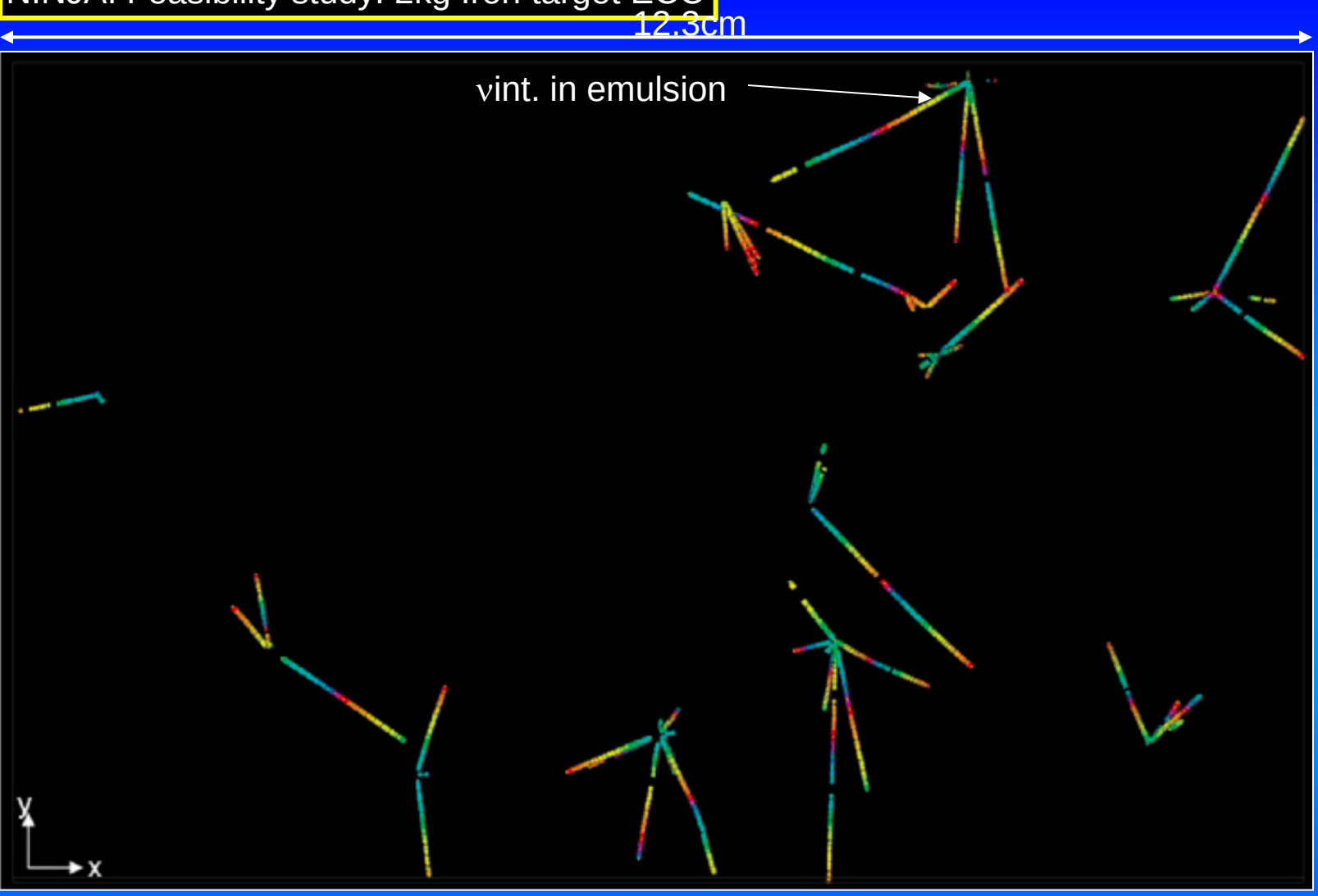
Emulsion film
25x38 cm^2 or 25x25cm^2
1～1.5 hours



Reconstructed track data



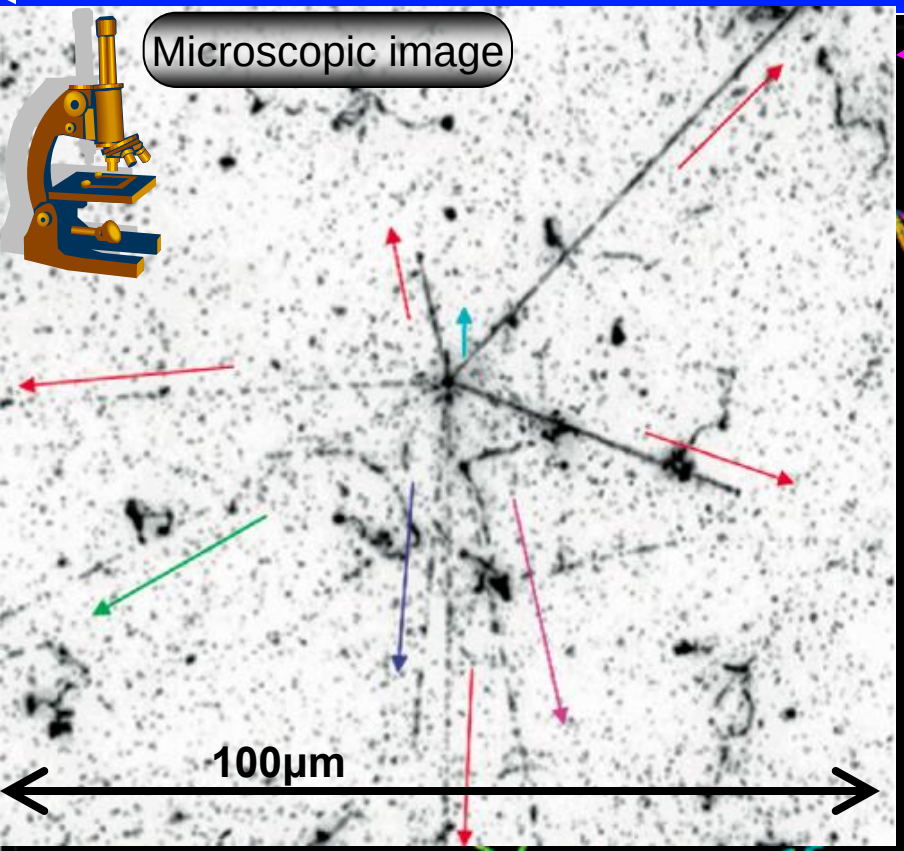
NINJA: Feasibility study: 2kg Iron target ECC

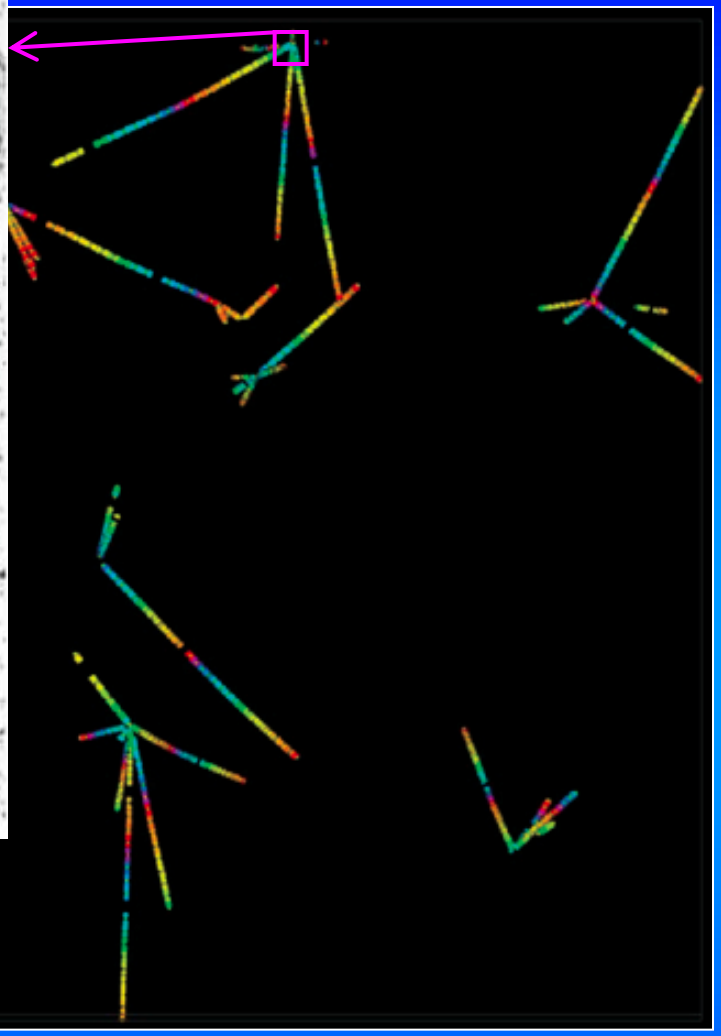


Iron 2.0cm

NINJA: Feasibility study: 2kg Iron target ECC

12.3cm

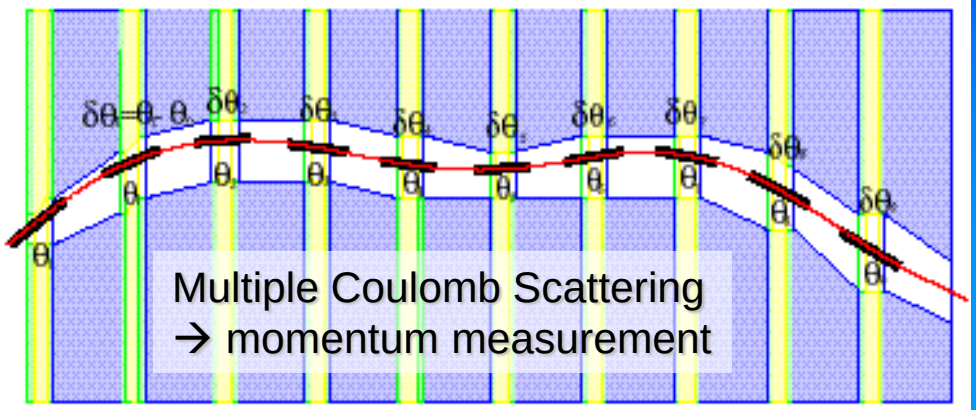




Iron 2.0cm

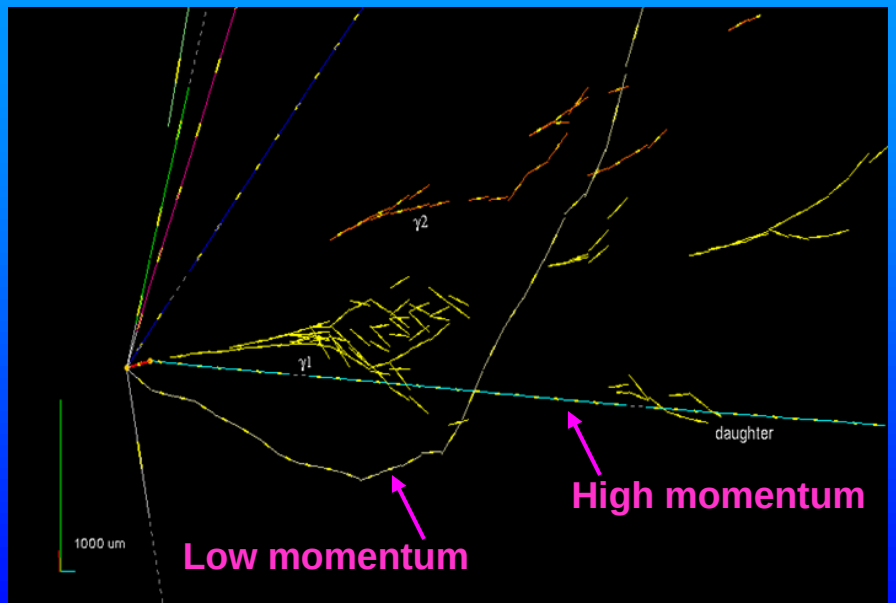
Momentum measurement

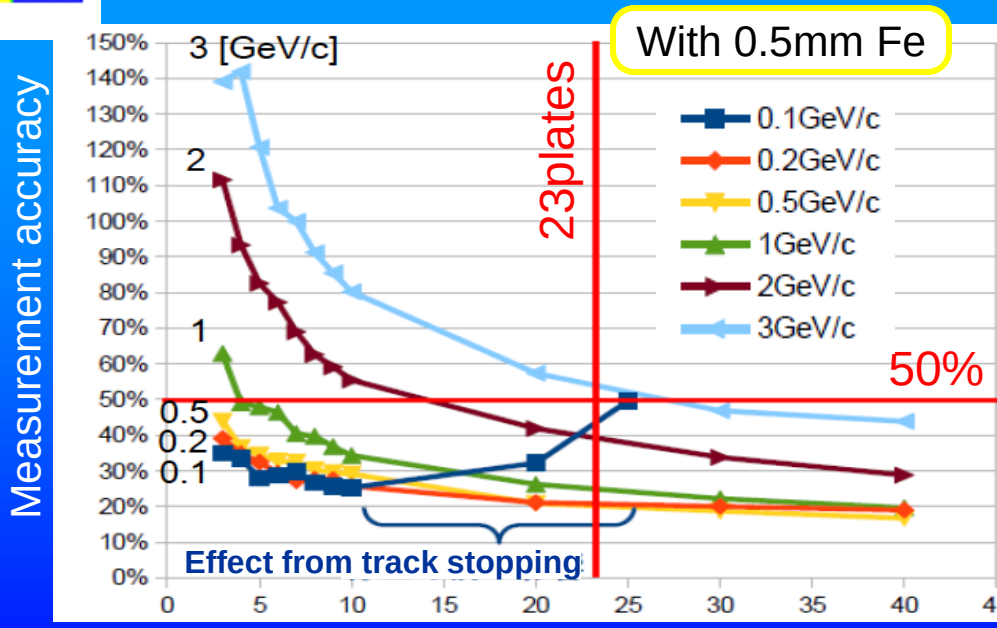
pβ measurement by the MCS method



$$P\beta = \frac{13.6\ (\mathrm{MeV/c})}{\sigma_{\delta\theta}}\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\frac{x}{X_0}\right)$$

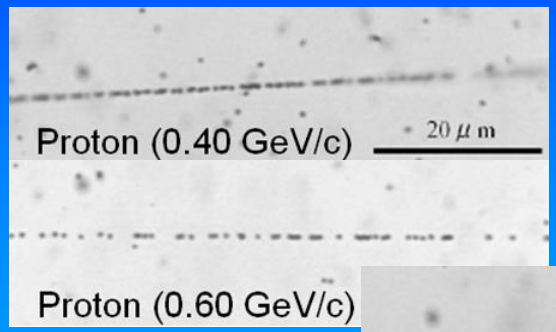
MC study by GEANT4

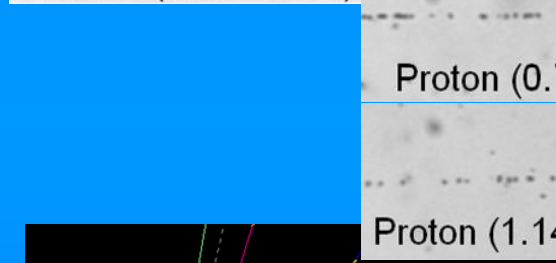


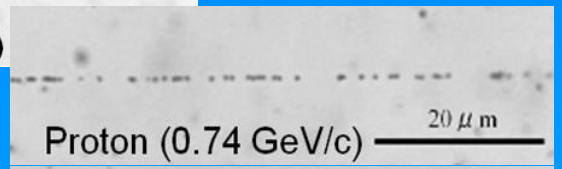


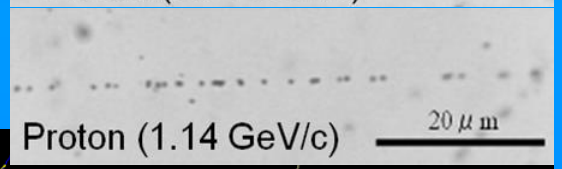
Proton identification

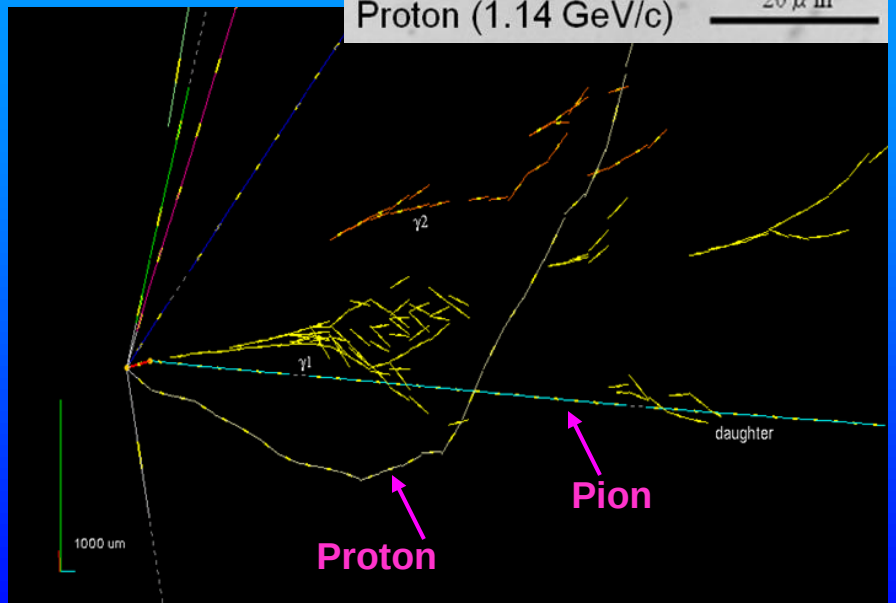
dE/dx measurement by track blackness

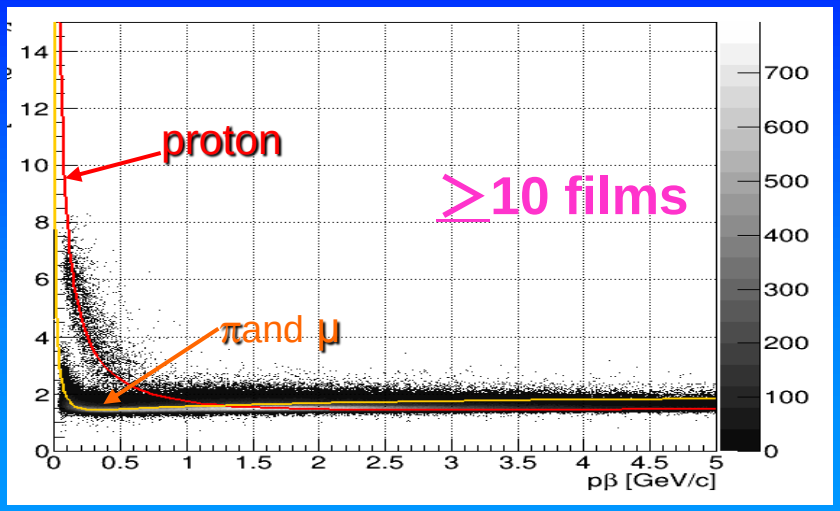




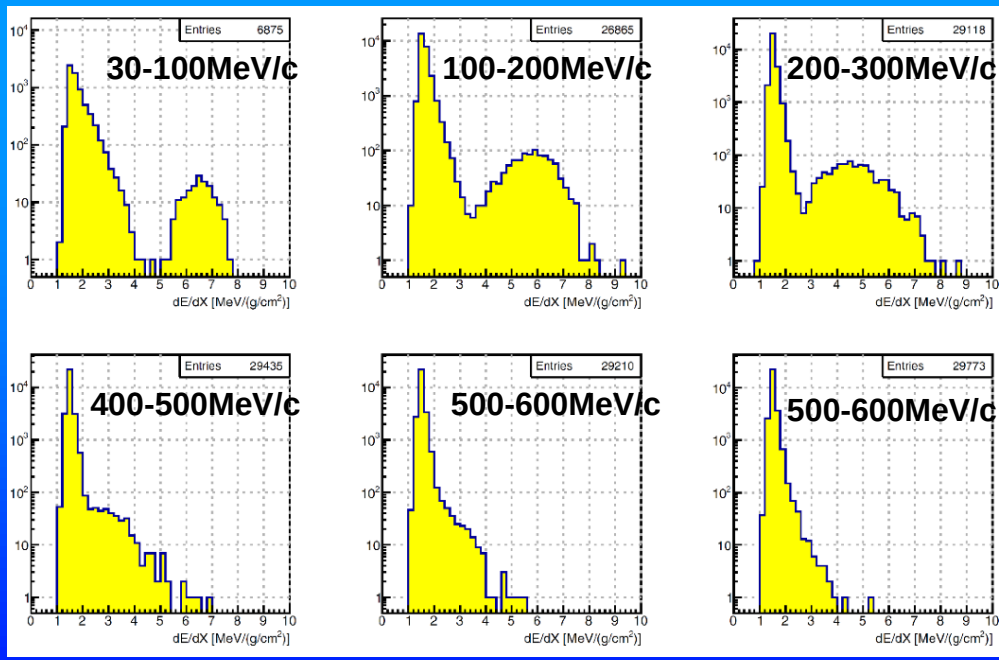








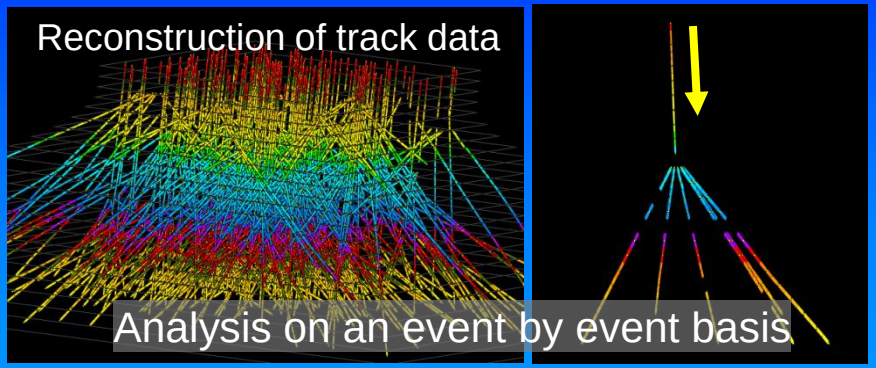
Momentum pβ (GeV/c)



More emulsion films, better separation

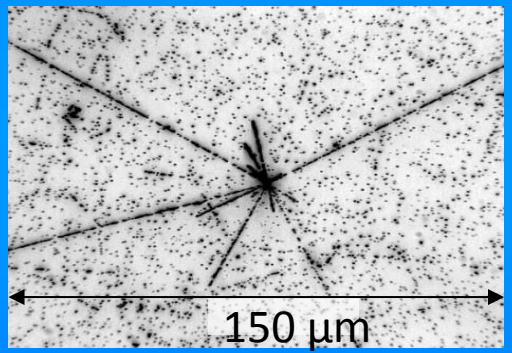
Nuclear Emulsion Detector

3D reconstruction

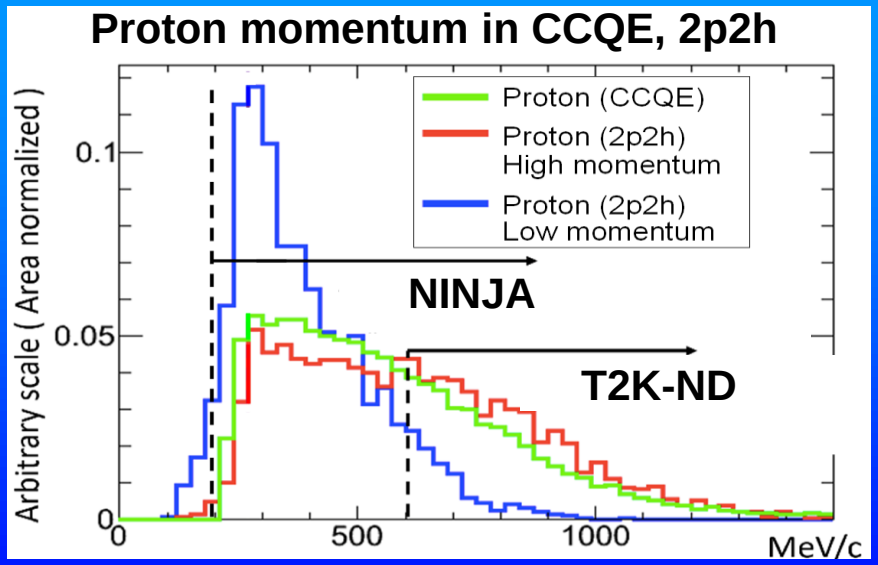


Scalability

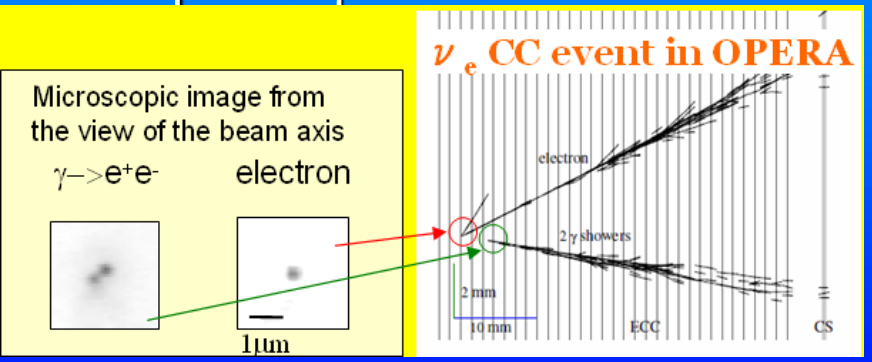
4π detection



Low energy threshold



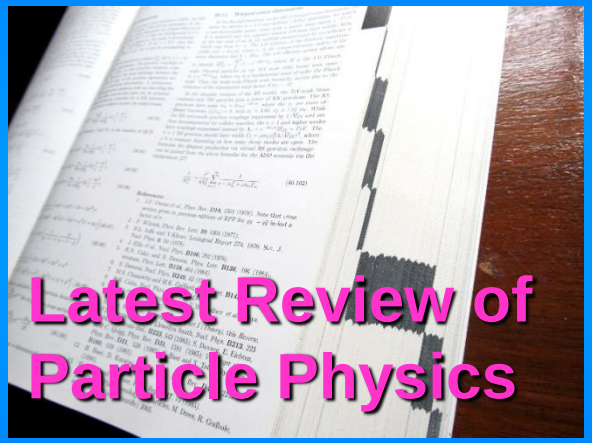
Good γ/π⁰ separation



Low BG from ν_μ NC π^0 production

Detector list of accelerator-based neutrino experiment

PDG particle data group



Latest Review of Particle Physics

Table 34.9: Properties of detectors for accelerator-based neutrino beams.

Name	Type	Target	Mass* (t)	Location	$\langle E_\nu \rangle$(GeV)	Dates
Lederman et al.	Spark	Al	10	BNL	0.2–2	1962
CERN-spark	Spark	Al	20	CERN	1.5	1964
Serpukhov	Spark	Al	20	IHEP	4	1977
Aachen-Padova	Spark	Al	30	CERN	1.5	1976–77
Gargamelle	Bubble	Freon	6	CERN	1.5,20	1972,1977
BEBC	Bubble	H,D,Ne-H	2–42	CERN	50,150 & 20	1977–84
SKAT	Bubble	Freon	8	IHEP	4	1977-1987
ANL-12ft	Bubble	H,D	1–2	ANL	0.5	1970
BNL-7ft	Bubble	H,D	0.4–0.9	BNL	1.3,3	1976–82
Fermilab-15ft	Bubble	D,Ne	1–20	FNAL	50,180&25,100	1974–92
CITF	Iron	Fe	92	FNAL	50,180	1977–83
CDHS	Iron	Fe	750	CERN	50,150	1977–83
MINOS	Iron	Fe	980,5.4k	FNAL	4–15	2005–2016
INGRID	Iron	Fe	99	J-PARC	0.7–3	2009–
Super-Kamiokande	Cherenkov	H_2O	22,500	Kamioka	0.6	1996–
K2K-1kt	Cherenkov	H_2O	25	KEK	0.8	1998–2004
MiniBooNE	Cherenkov	CH_2	440	FNAL	0.6	2002–12
HWPF	Scintillation	CH_2	2	FNAL	2	2014–
LSND	Scintillation	CH_2	130	LANL	0.06	1993–98
NOvA	Scintillation	CH_2	300,14k	FNAL/Ash River	2	2013–
SciBar	Scintillation	CH	12	KEK/FNAL	0.8,0.6	2004,2007–8
ICARUS	LArTPC	Ar	760	LNGS	20	2006–12
Argoneut	LArTPC	Ar	0.025	FNAL	3	2009–10
MicroBooNE	LArTPC	Ar	170	FNAL	0.8	2014–
FNAL-E-531	Emulsion	Ag, Br	0.009	FNAL	25	1984
CHORUS	Emulsion	Ag, Br	1.6	CERN	20	1995
DONuT	Emulsion	Fe	0.26	FNAL	100	1997
OPERA	Emulsion	Pb	1.3k	LNGS	20	2006–12
NINJA	Emulsion	Fe	0.001	J-PARC	0.6	2016–
[illegible]	[illegible]	[illegible]	[illegible]	CERN	20	1977
[illegible]	[illegible]	[illegible]	[illegible]	CERN	20	1983
[illegible]	[illegible]	[illegible]	[illegible]	BNL	1.3	1987
[illegible]	[illegible]	[illegible]	[illegible]	BNL	3	1990
NOMAD	Hybrid	CH	3	CERN	20	1995–98
CCFR	Hybrid	Fe	690	FNAL	90,260	1991
NuTeV	Hybrid	Fe	690	FNAL	70,180	1996–97
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2009–
[illegible]	[illegible]	[illegible]	[illegible]	J-PARC	[illegible]	2009–

* Fiducial.

NINJA

detector, with 1,300 t of emulsion, to make the first direct observation of the appearance of ν_τ in a ν_μ beam. Recently, the NINJA collaboration has developed an emulsion cloud chamber detector to observe neutrinos in the J-PARC neutrino beam [227].

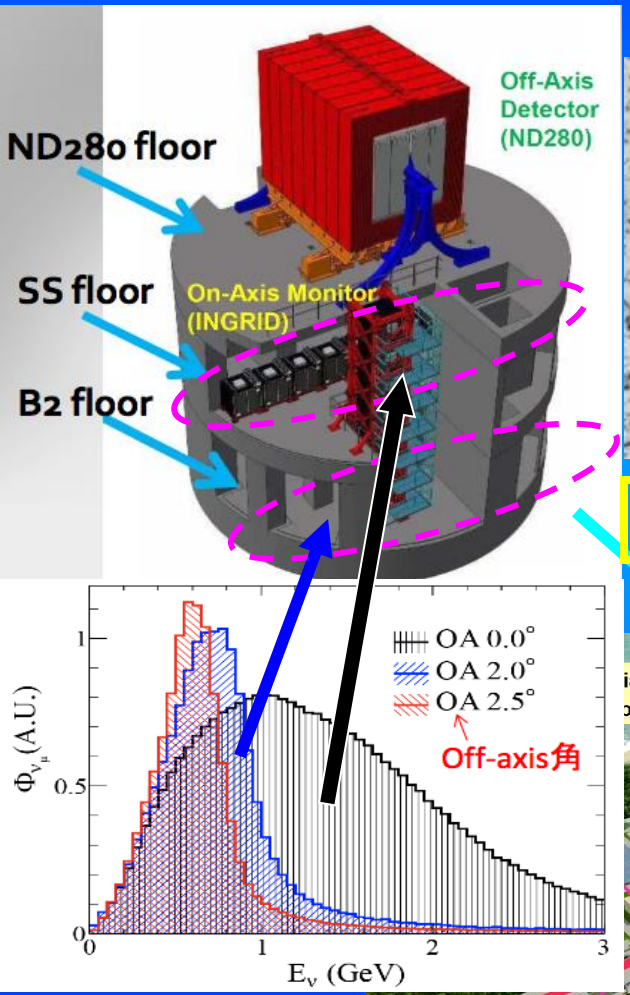
227. T. Fukuda *et al.*, PTEP **2017**, no. 6, 063C02 (2017).

We hope to publish our cross-section results

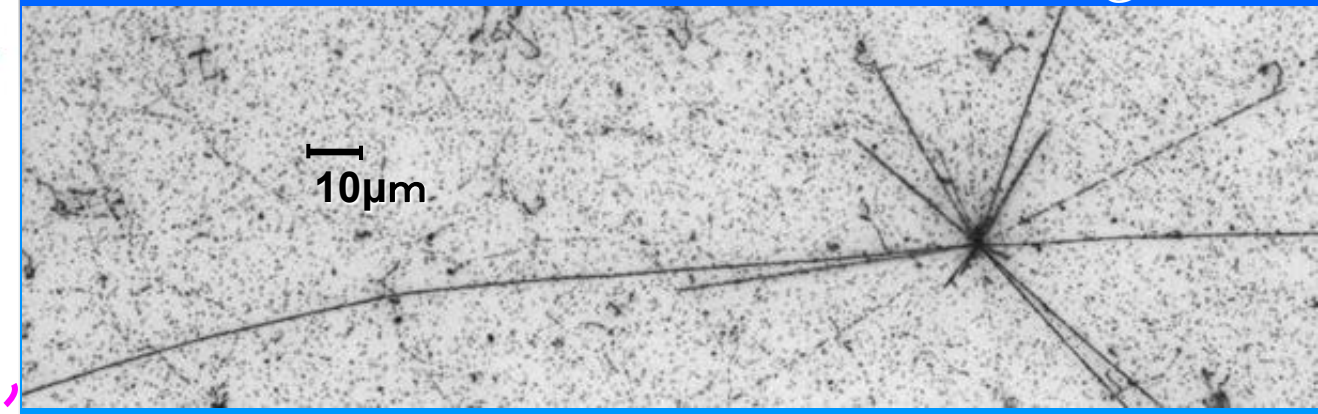
NINJA

NINJA Experiment

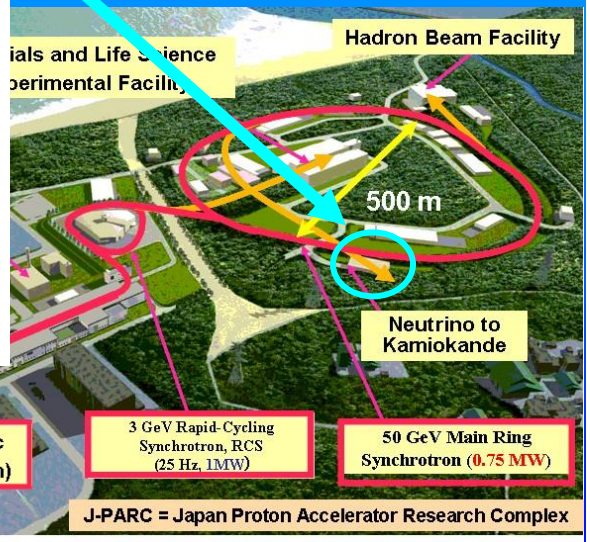
Neutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator



A neutrino interaction in emulsion @J-PARC



A collaborative project with some member of OPERA and T2K



Working group

OPERA — **J-PARC** — **T2K**

Experimental site, Neutrino beam

- **Nihon Univ.** — Emulsion development
- **Univ. Tokyo** — T2K near detector
- **Nagoya Univ.** — Film production, Scan
- **Kyoto Univ.** — T2K near detector
- **Toho Univ.** — Film production, Scan
- **Yokohama N Univ.** — T2K near detector
- **Kobe Univ.** — Emulsion Shifter
- **ICRR** — Neutrino simulation

NINJA Collaboration

Nihon University: Y. Hanaoka, T. Kanayama, K. Kashiwabara, S. Mikado (* Spokesperson)

Nagoya University: T. Fukuda*, H. Kawahara, R. Komatani, M.Komatsu, M. Komiyama, K. Morishima, M. Naiki, M. Nakamura, Y. Nakamura, N. Naganawa, N. Nakano, T. Nakano, A. Nishio, H. Rokujo, O. Sato, K. Sugimura, L. Suzui, Y. Suzuki, T. Takao, R. Watanabe

Toho University: T. Matsuo, K. Mizuno, Y. Morimoto, S. Ogawa, H. Oshima, H. Takagi, H. Shibuya

Kobe University: S. Aoki

ICRR, University of Tokyo: Y. Hayato

Yokohama National University: A. Minamino, G. Pintaudi, Y. Tanihara

Kyoto University: A. Ajmi, A. Hiramoto, A. K. Ichikawa, T. Kikawa, T. Nakaya, T. Odagawa, K. Yasutome

University of Tokyo: M. Yokoyama

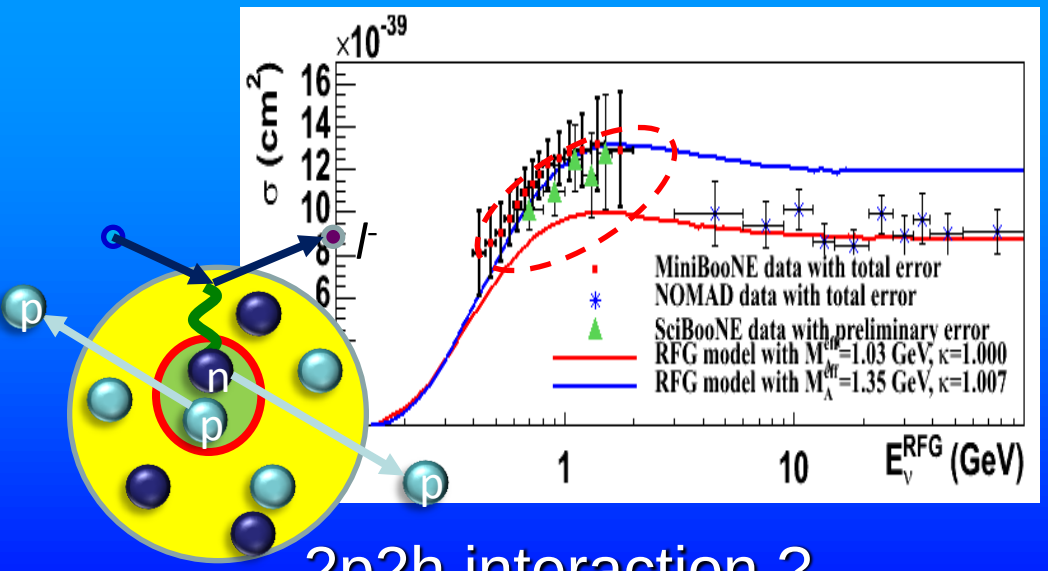
Physics Motivation

Sub-Multi GeV Neutrino interaction

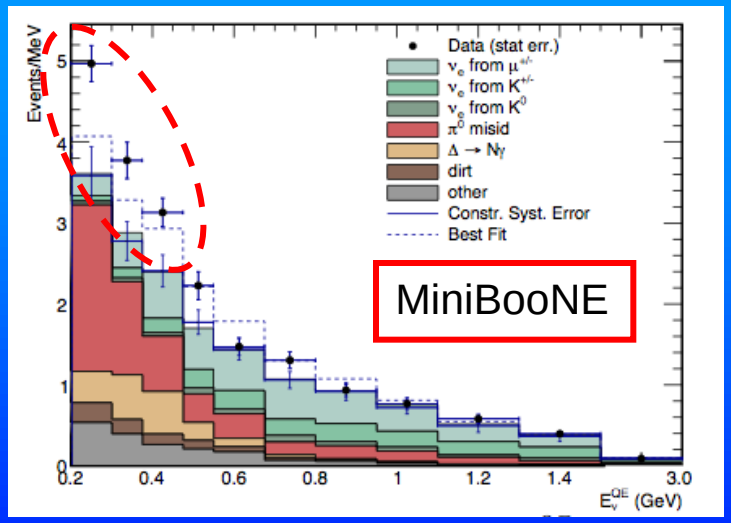
- Major source of uncertainty in νoscillation analysis
- ν_e anomaly from several experiments (sterile ν ?)

Need to more understand the neutrino-nucleus interaction !

1. Confirmation and cross-section measurement of 2p2h int.
2. Exclusive measurement of ν_μ, ν_e- water cross-sections

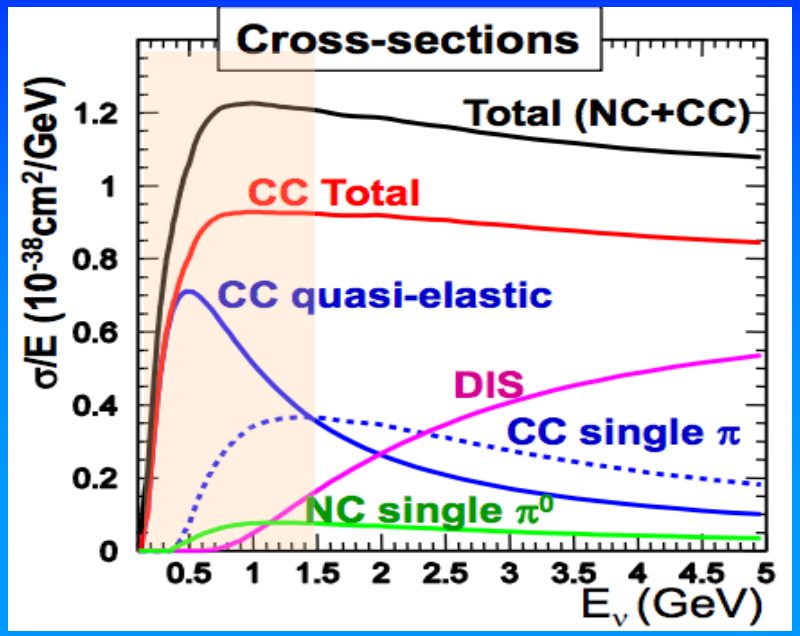


2p2h interaction ?

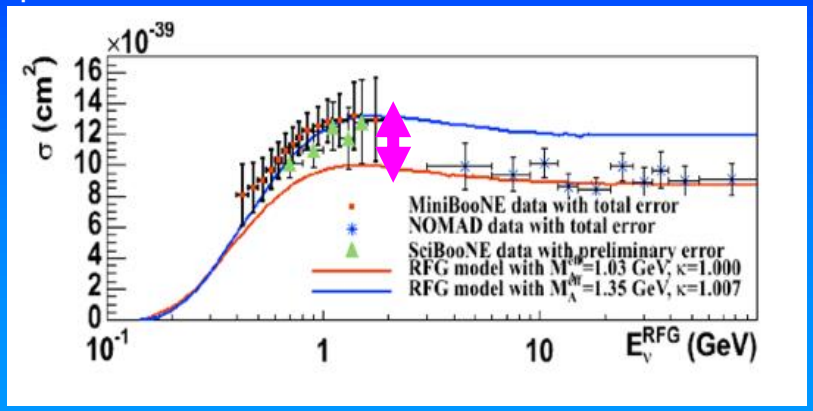


Effect from Sterile Neutrino ?

Low energy neutrino interactions

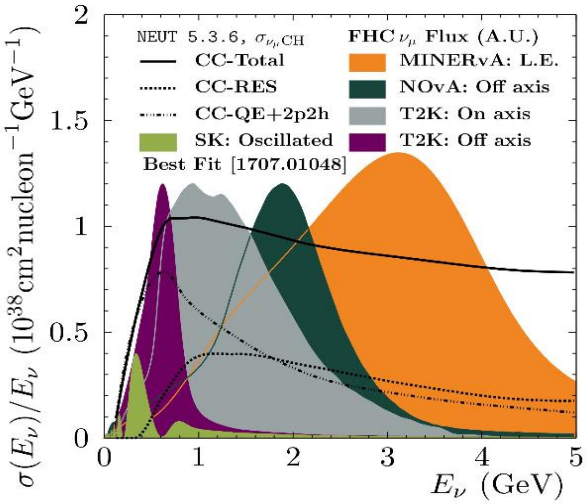


ν_μ-Carbon CCQE like cross-section



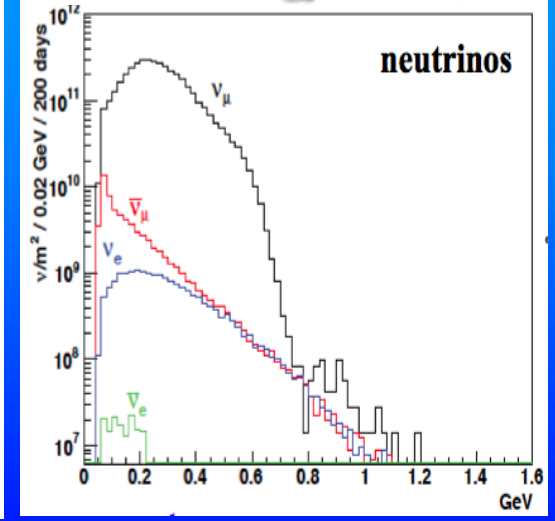
There are discrepancy between low and high energy

Neutrino energy for current experiments

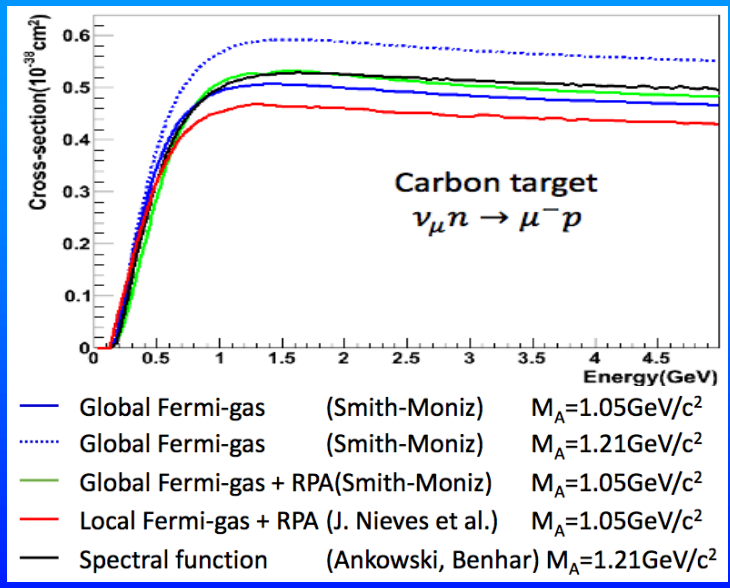


L. Pickering, NuFact2019

ESSvSB ν energy distribution



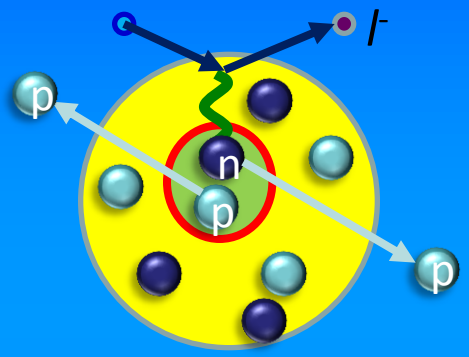
M. Dracos, NuFact2019



Y. Hayato, NuInt2018

Multi-nucleon reaction (2p2h)

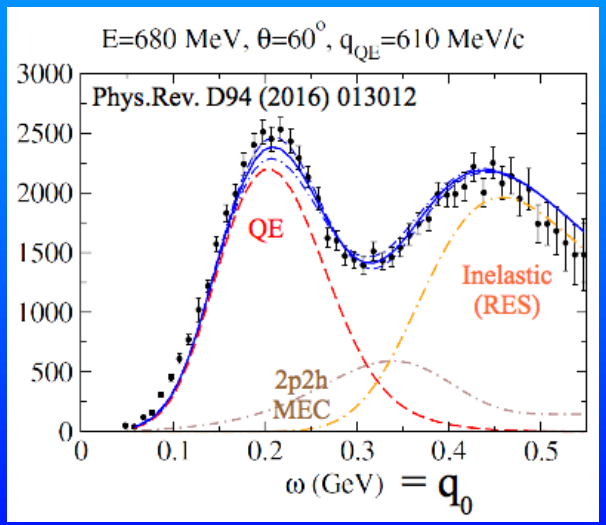
In cross-section of CCQE-like events, measured value is much larger than the simple model predictions → new interaction process (2p2h) ?



- **There is experimental indication of binding nucleon pair from electron scattering experiment.**
  → Need to apply in neutrino scattering experiment.
- **2p2h is judged as CCQE with the detector which can not detect protons.**

Neutrino energy reconstruction of CCQE like event at far detector is wrong if 2p2h process is exist.
→ large systematic uncertainty

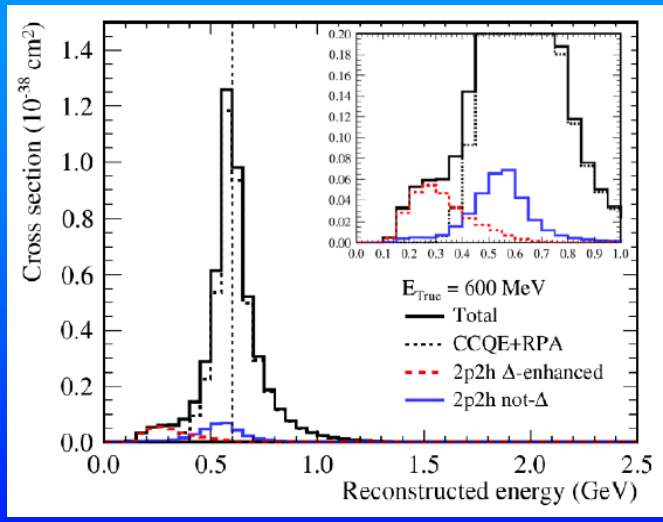
Electron scattering experiment



CCQE: $\nu_\mu + n \rightarrow \mu^- + p$
→ 2 body reaction

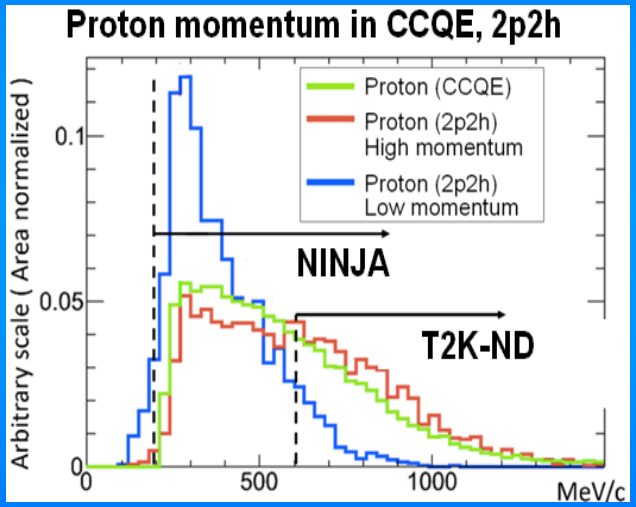
2p2h: **2protons are emitted**
$\nu_\mu + (n, p) \rightarrow \mu^- + p + p$
→ 3 body reaction

Proton measurement is important to more understand

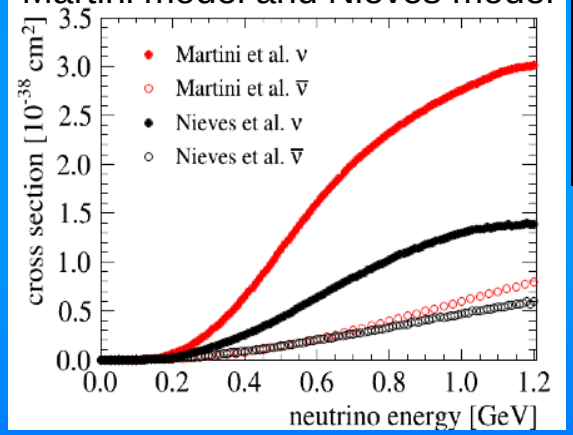


Low energy proton measurement

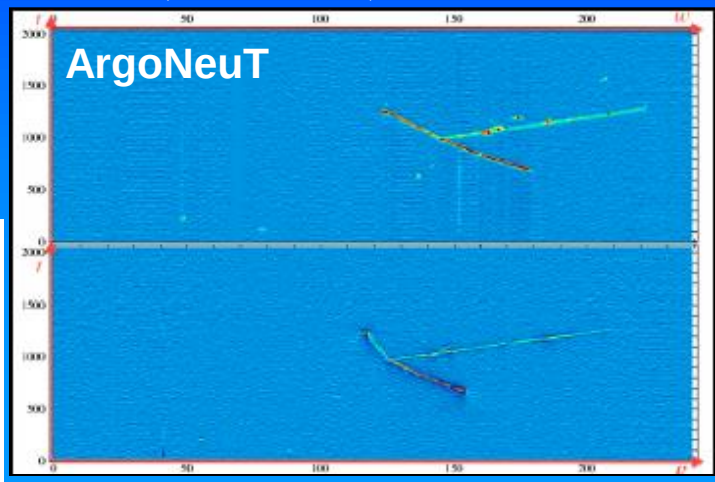
- **Some general models predict that back-to-back protons are emitted from binding nucleon pair in neutrino event.**
- **Large model dependence.**



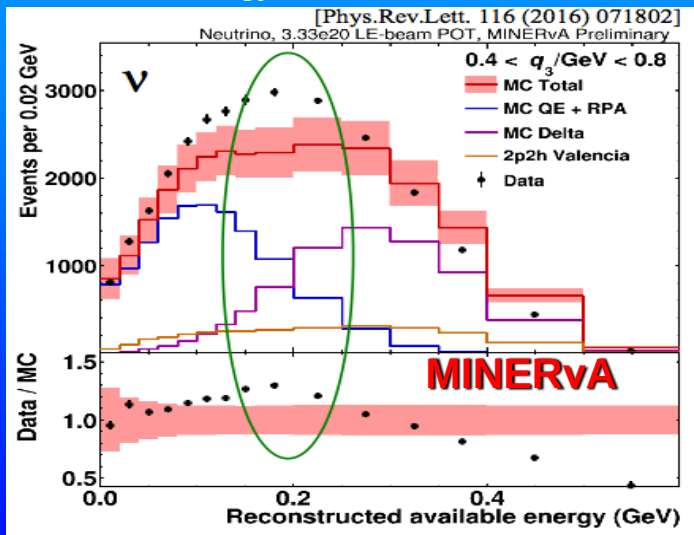
Cross-section of 2p2h in Martini model and Nieves model



Back-to-back proton event in Liquid Argon detector（low statistics）



2p2h-like enhancement in reconstructed neutrino energy in ＜Ev＞~3GeV

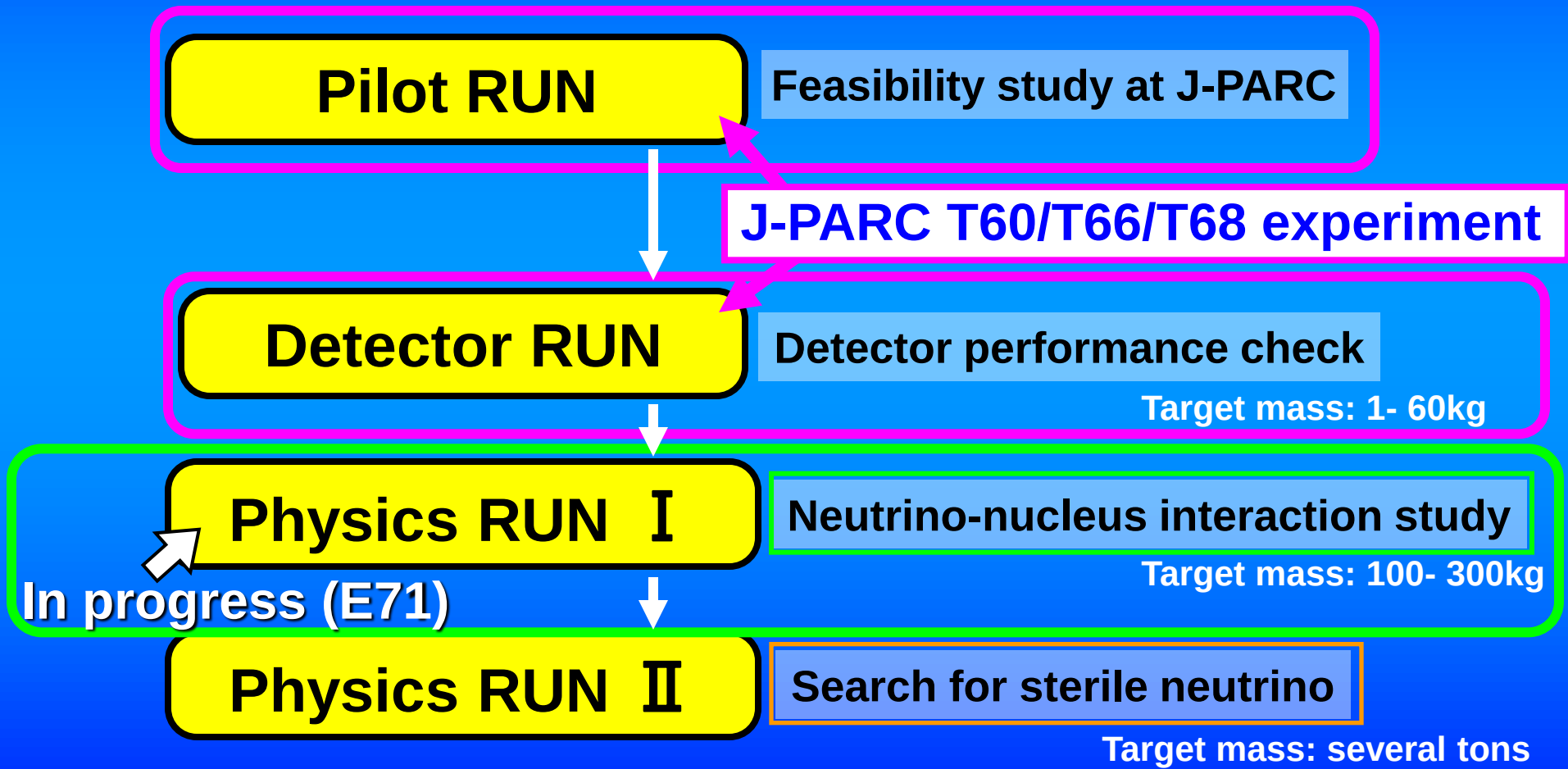


Emulsion detector can detect low energy protons for several materials, including water.
→ New precision information

Proton information is also useful to understand not only 2p2h, but also simple CCQE.

Roadmap

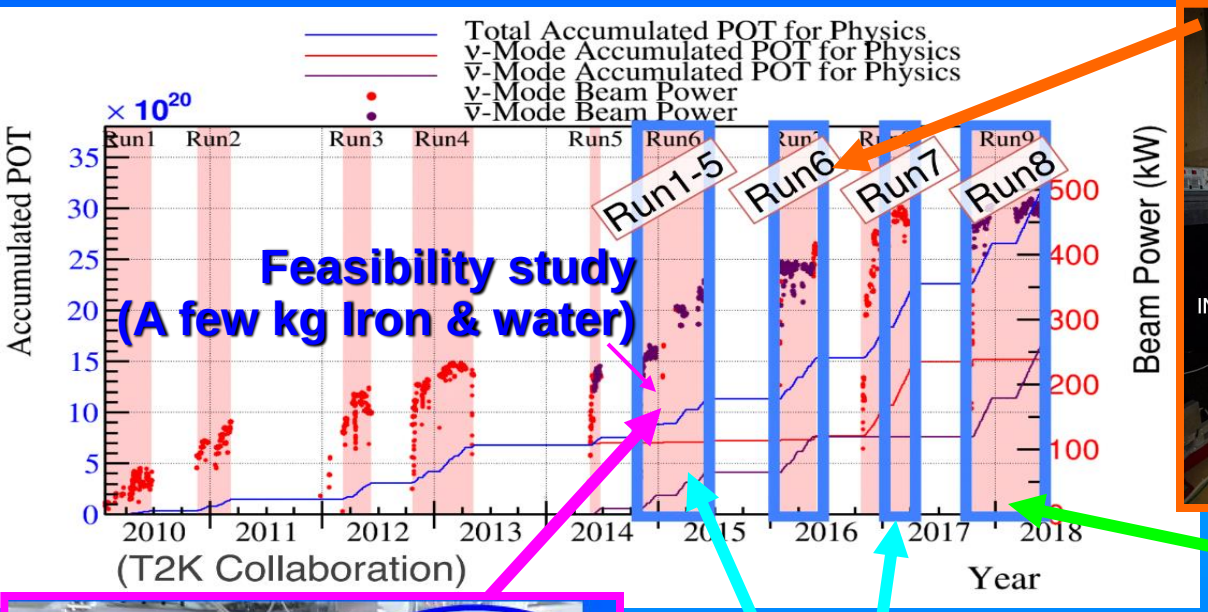
Since the end of 2014, we have demonstrated the basic performance of emulsion detector in test experiments.

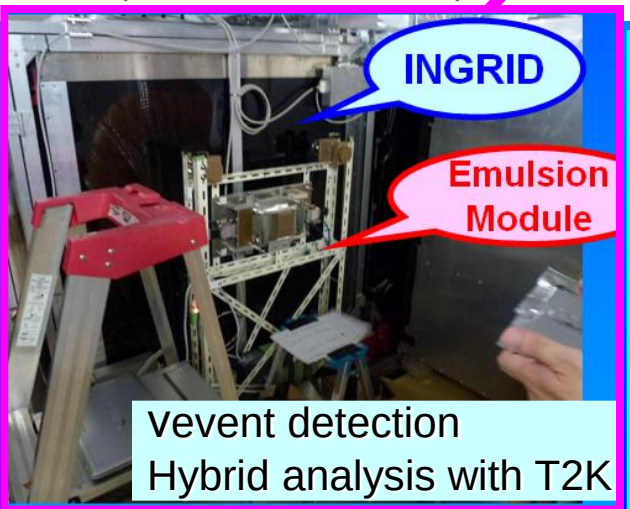


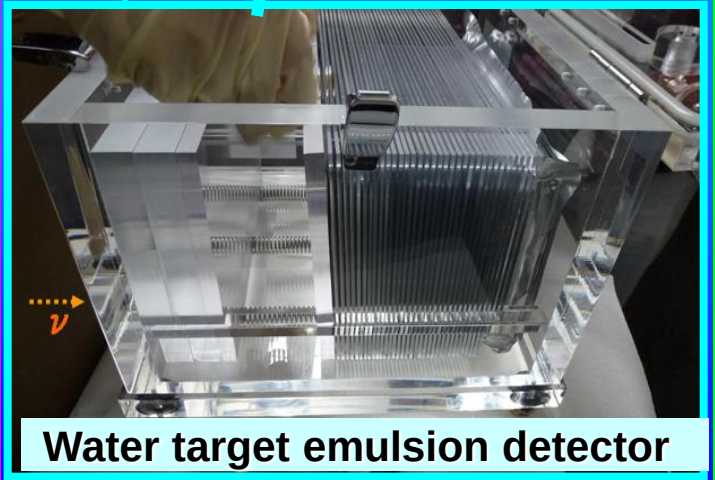
Physics run will be started from Nov. 2019.

ν exposure of NINJA

Since the end of 2014, we have demonstrated the basic performance of emulsion detector in test experiments.

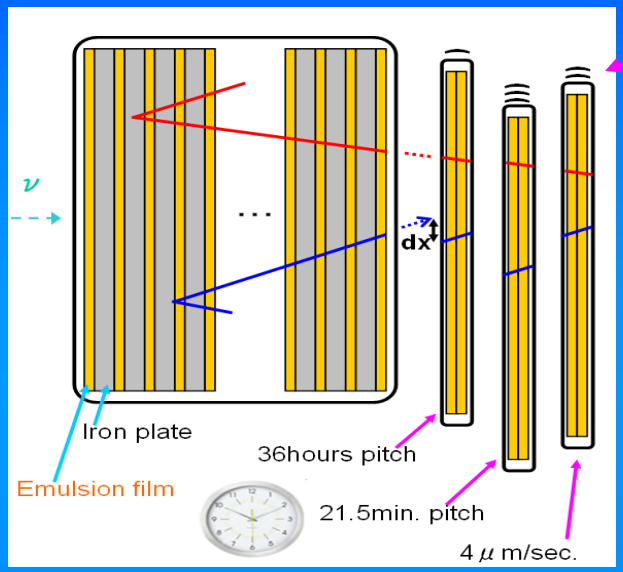






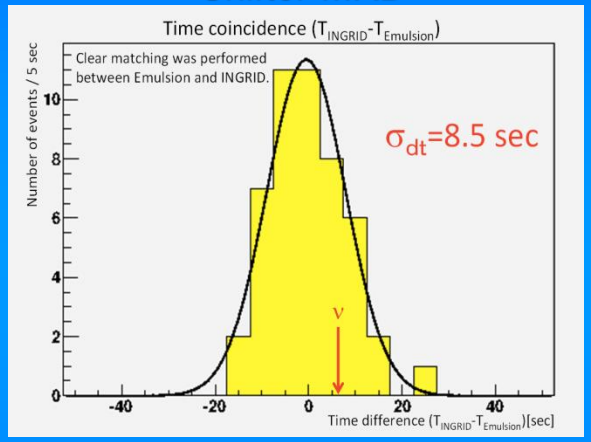
Detector Run: Iron ECC + ES + MRD

Target: Iron~40kg, Beam: 0.4x10^{20}POT Neutrino mode

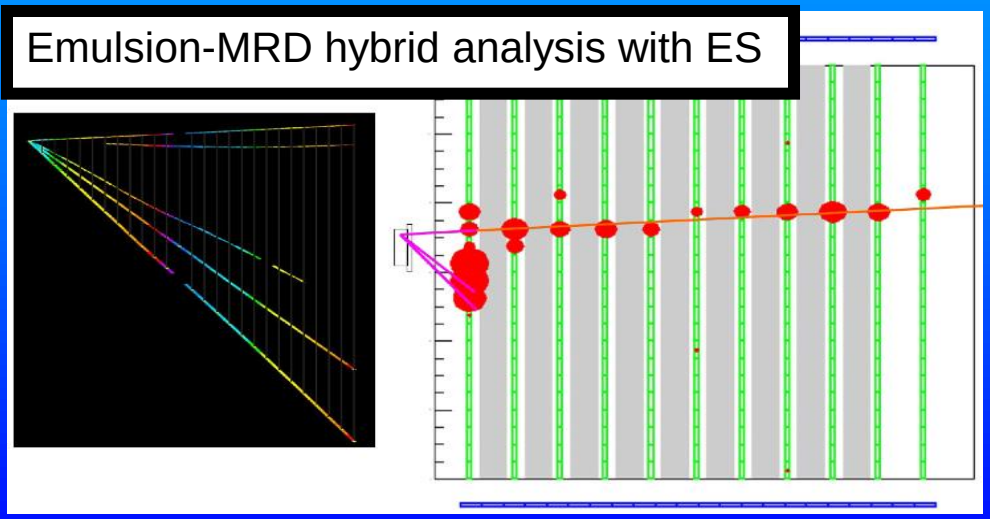


Emulsion Shifter

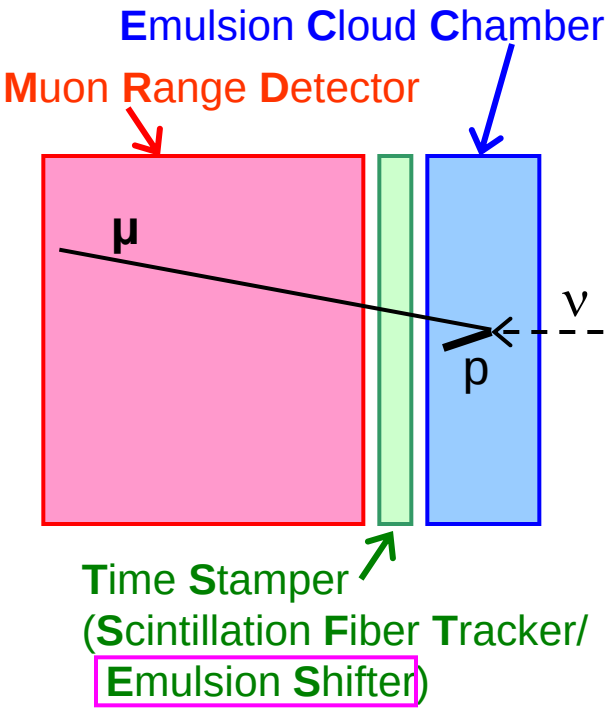
Shifter-MRD



Emulsion-MRD hybrid analysis with ES



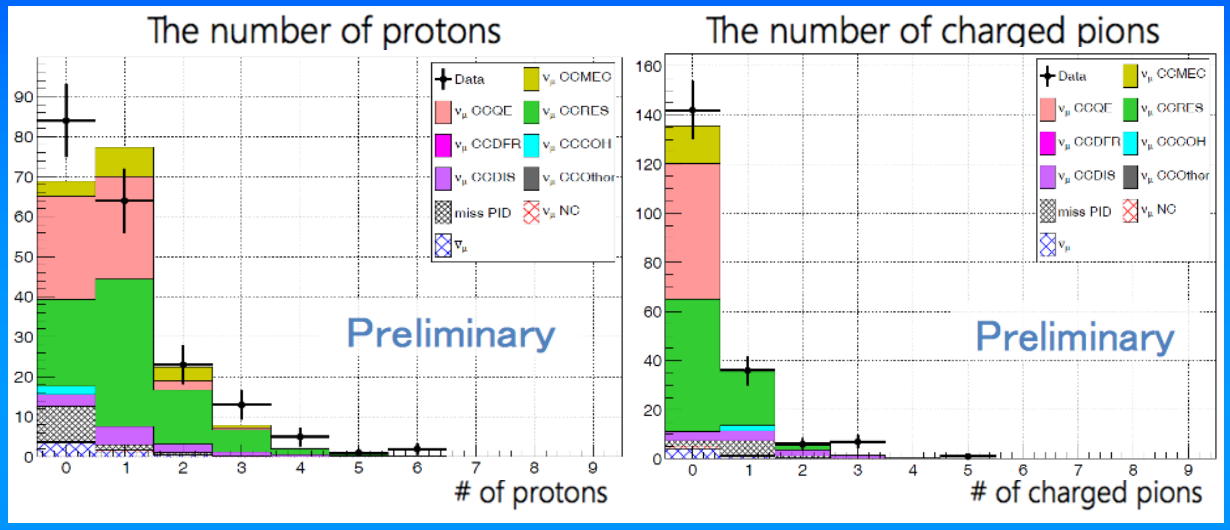
Conceptual design

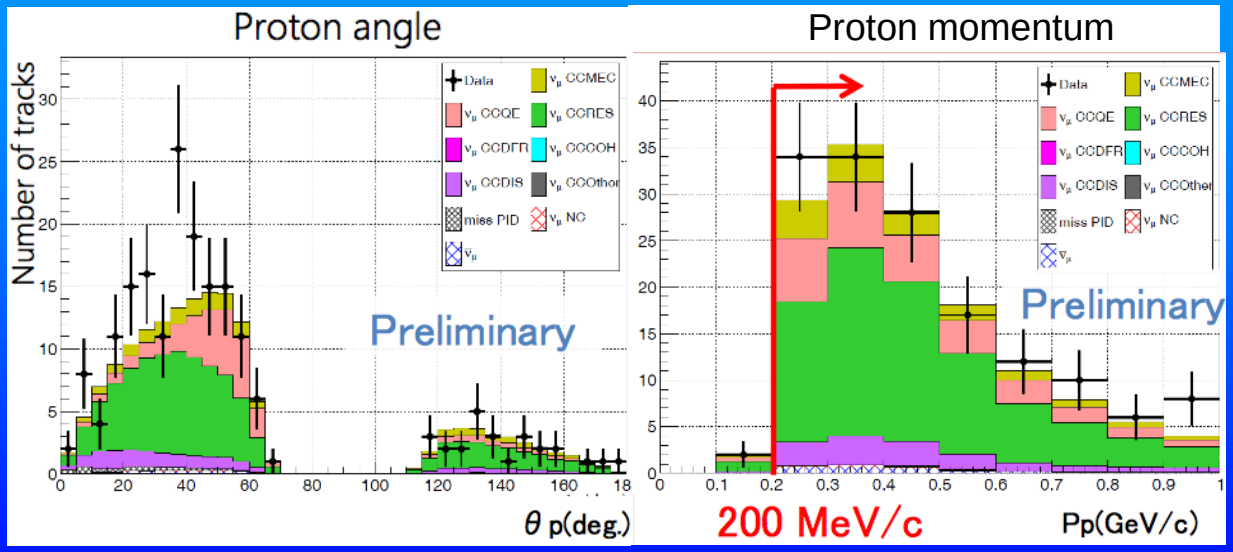


ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

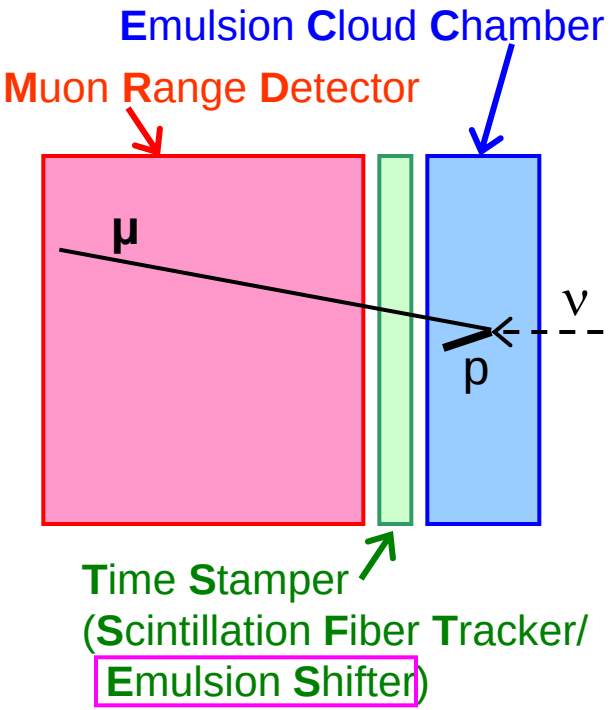
Detector Run: Iron ECC + ES + MRD

Target: Iron~40kg, Beam: 0.4x10^{20}POT Neutrino mode





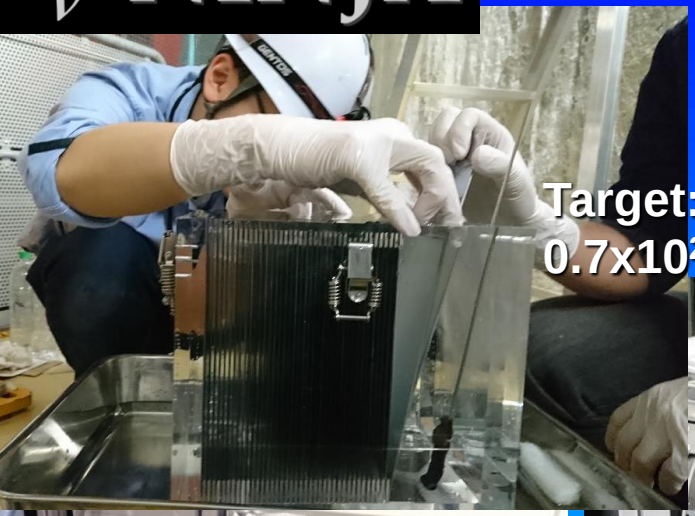
Conceptual design



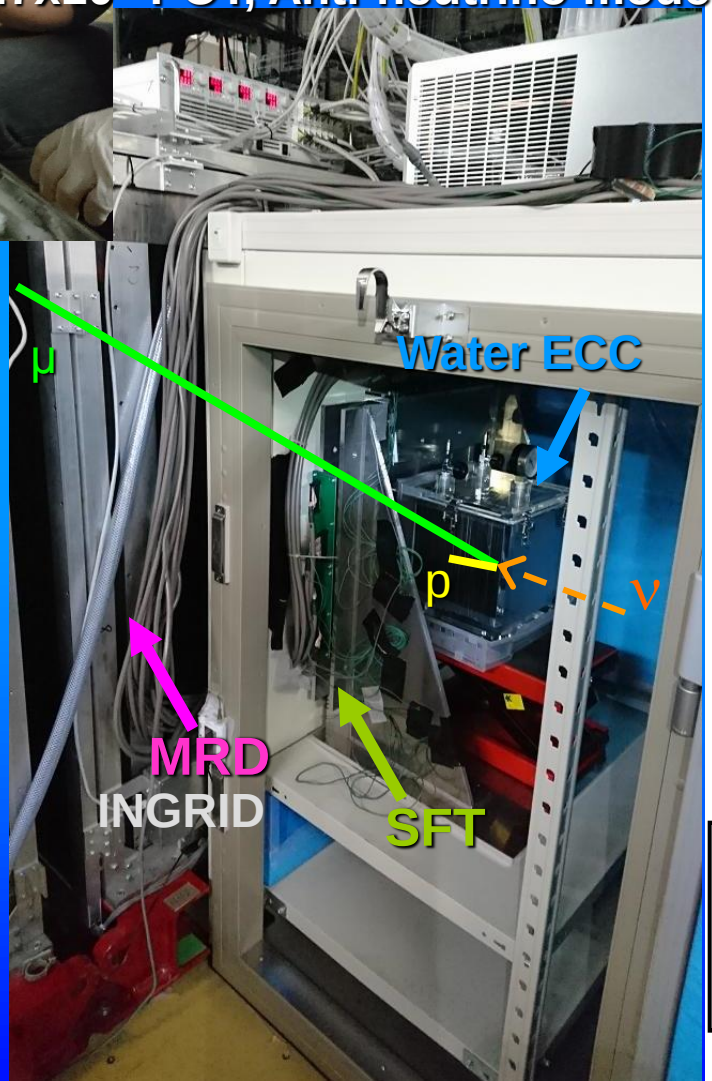
ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

NINJA

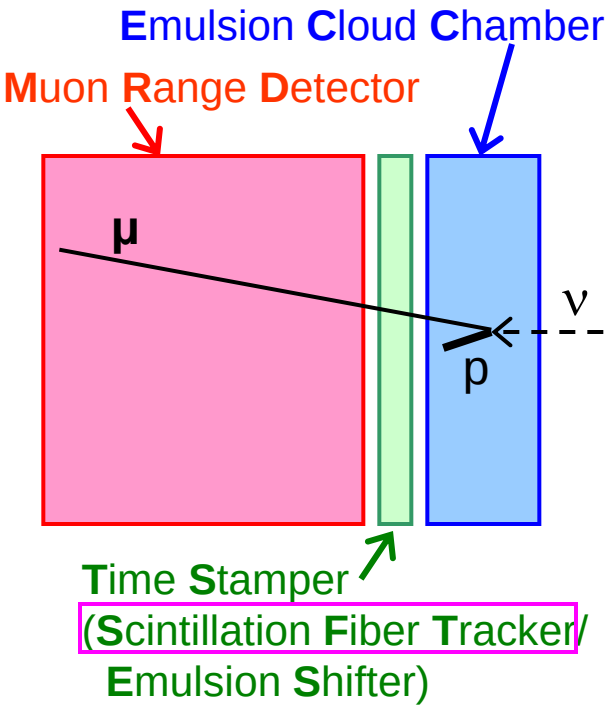
Detector Run: Water ECC + SFT + MRD



Target: Water~4kg,
0.7x10^{21}POT, Anti-neutrino mode

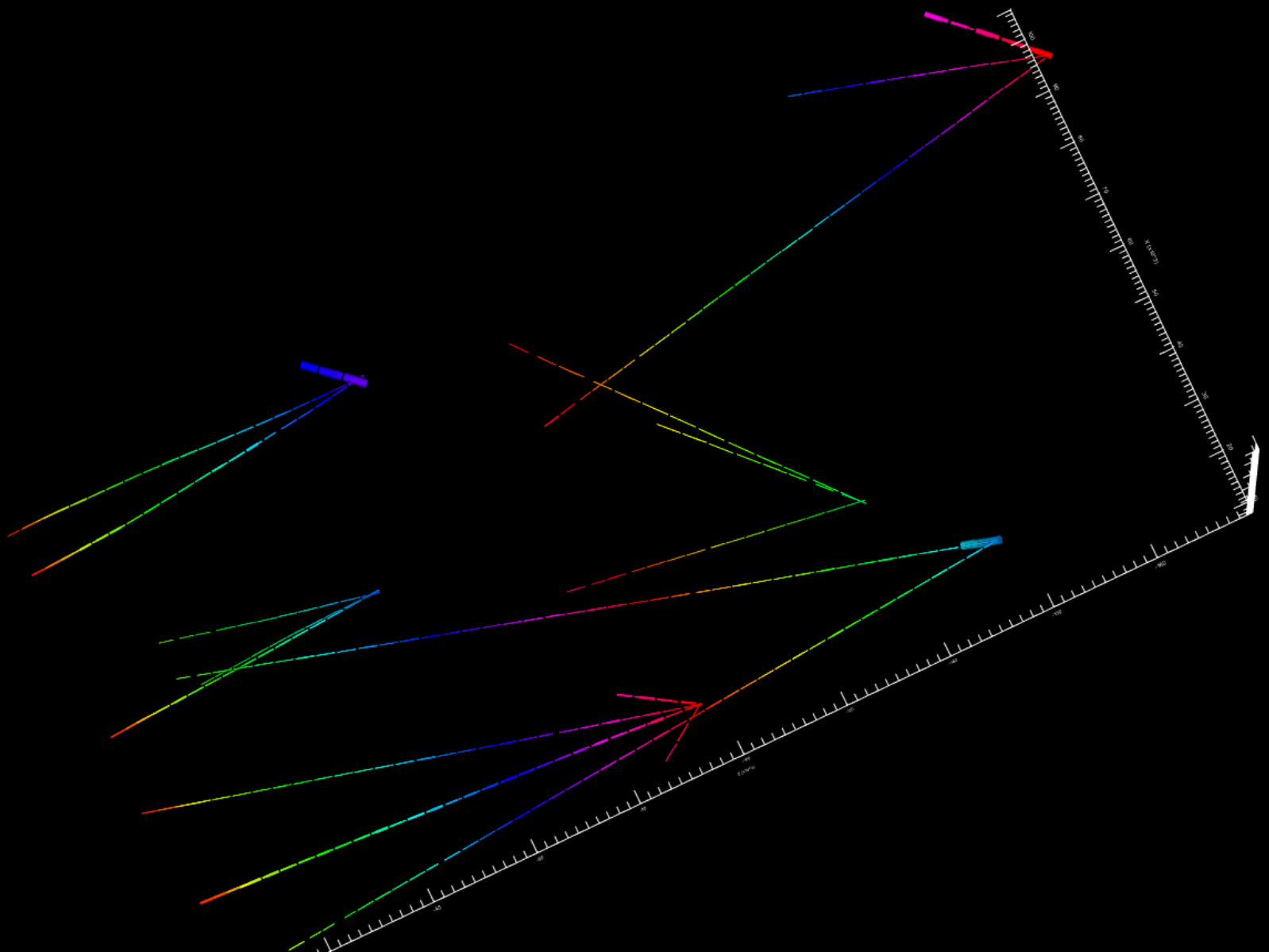


Conceptual design



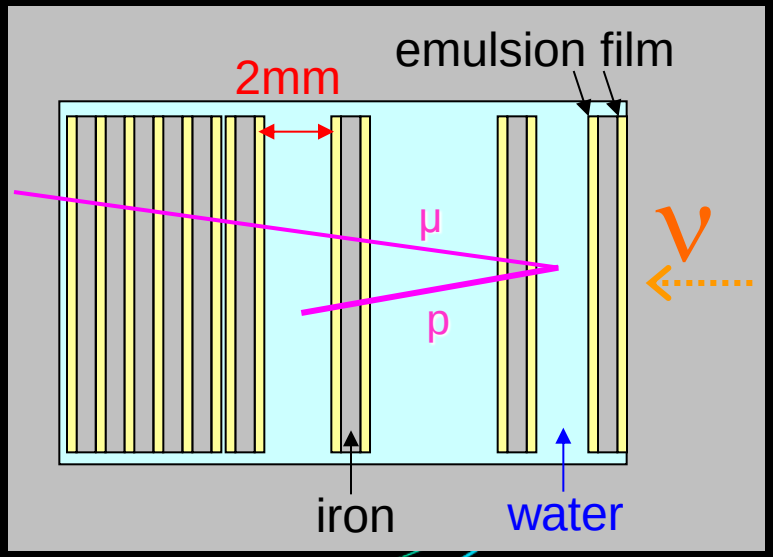
ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

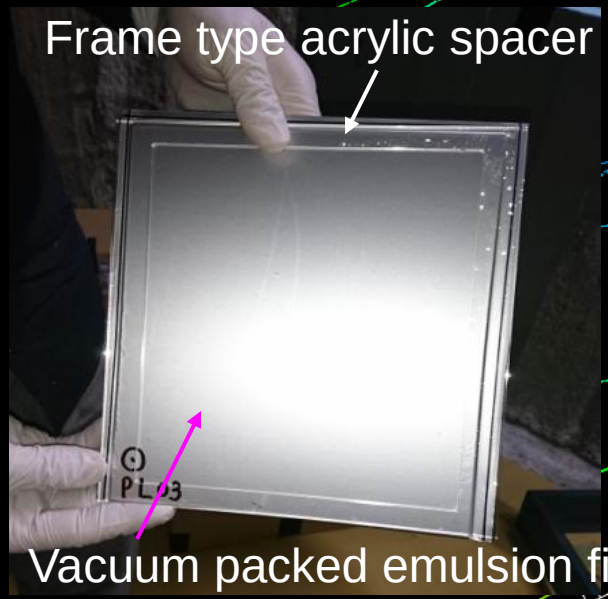
$\bar{\nu}$-water interactions



NINJA

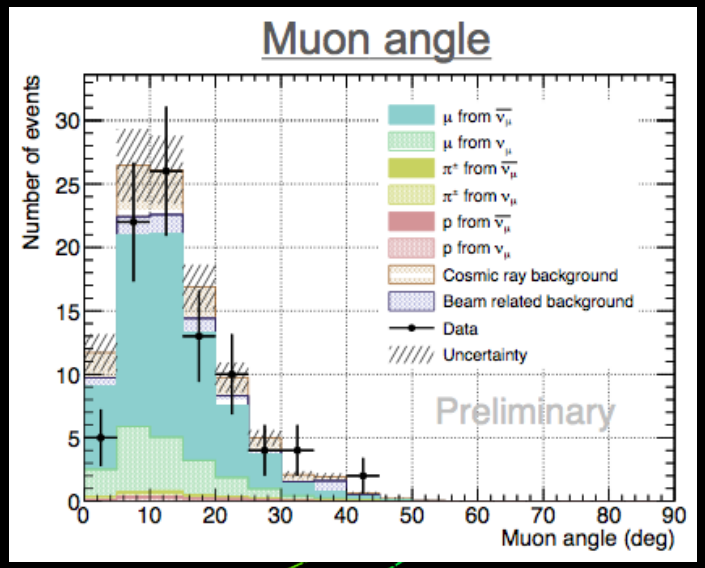
$\bar{\nu}$-water interactions

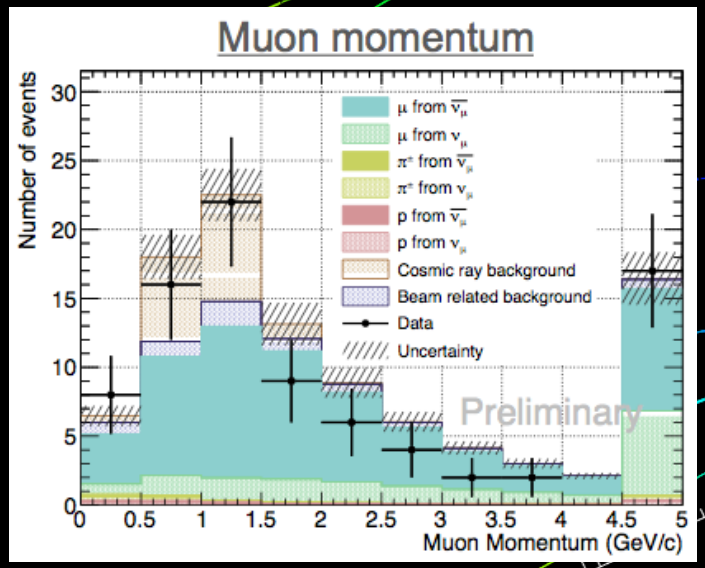


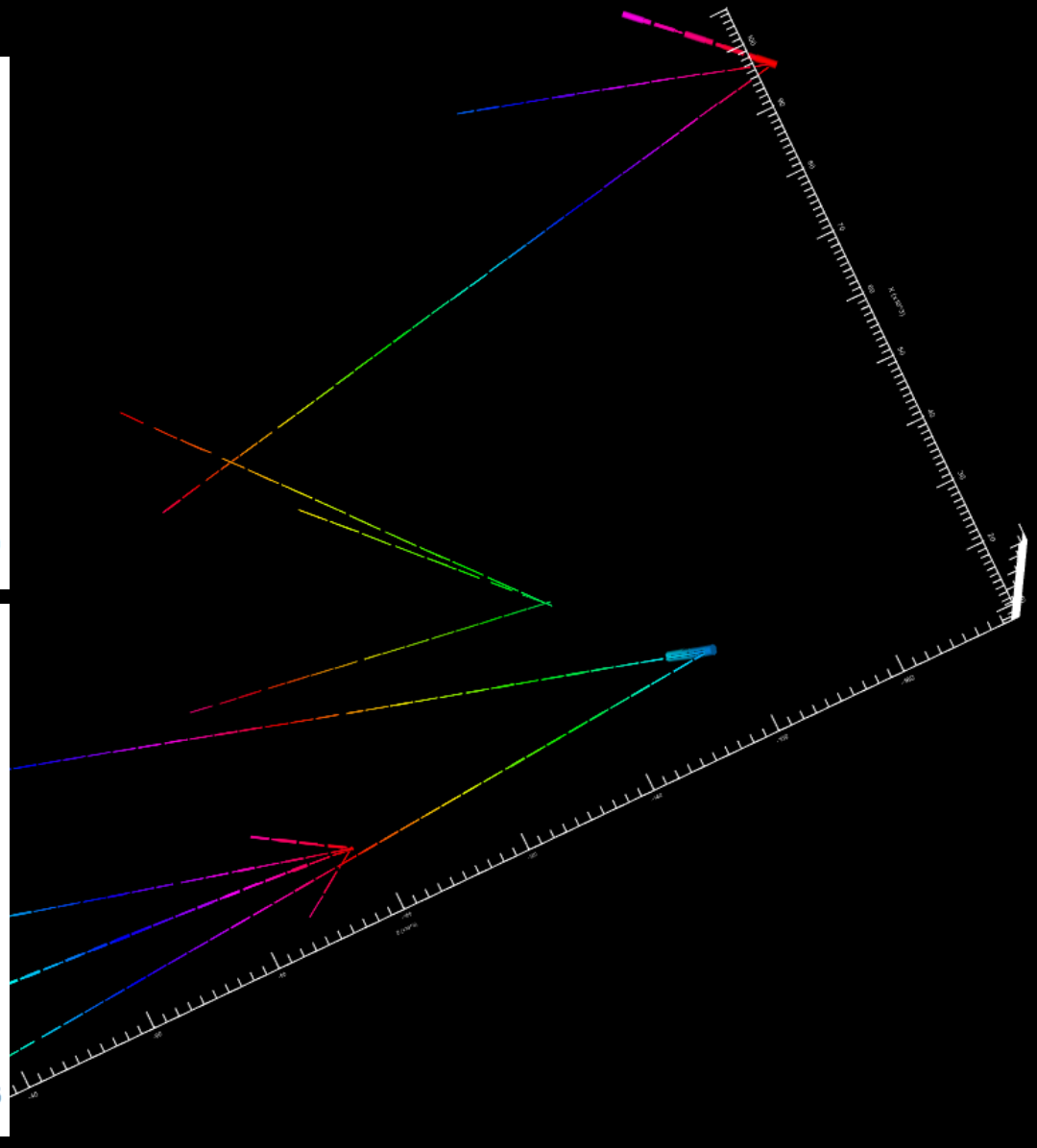


NINJA

$\bar{\nu}$-water interactions

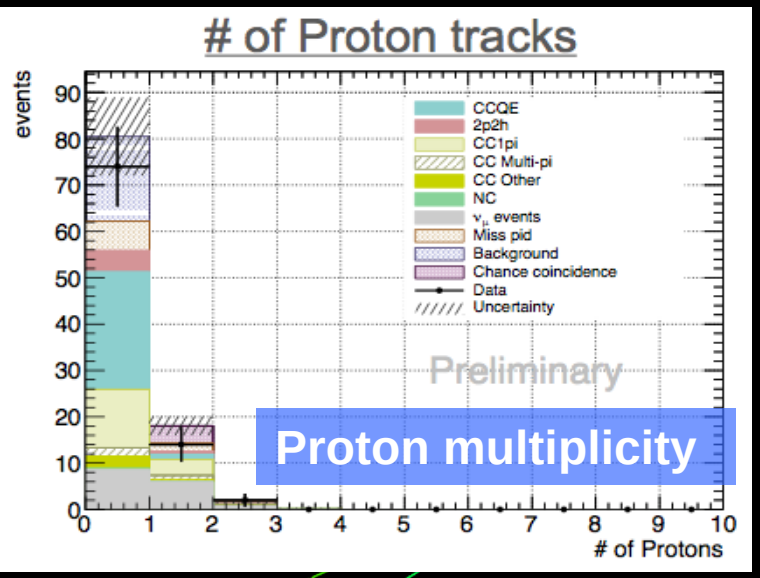




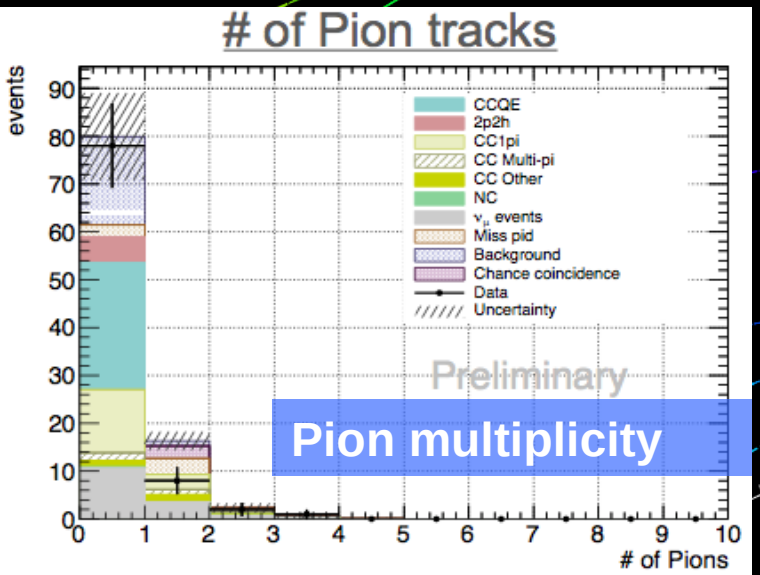


NINJA

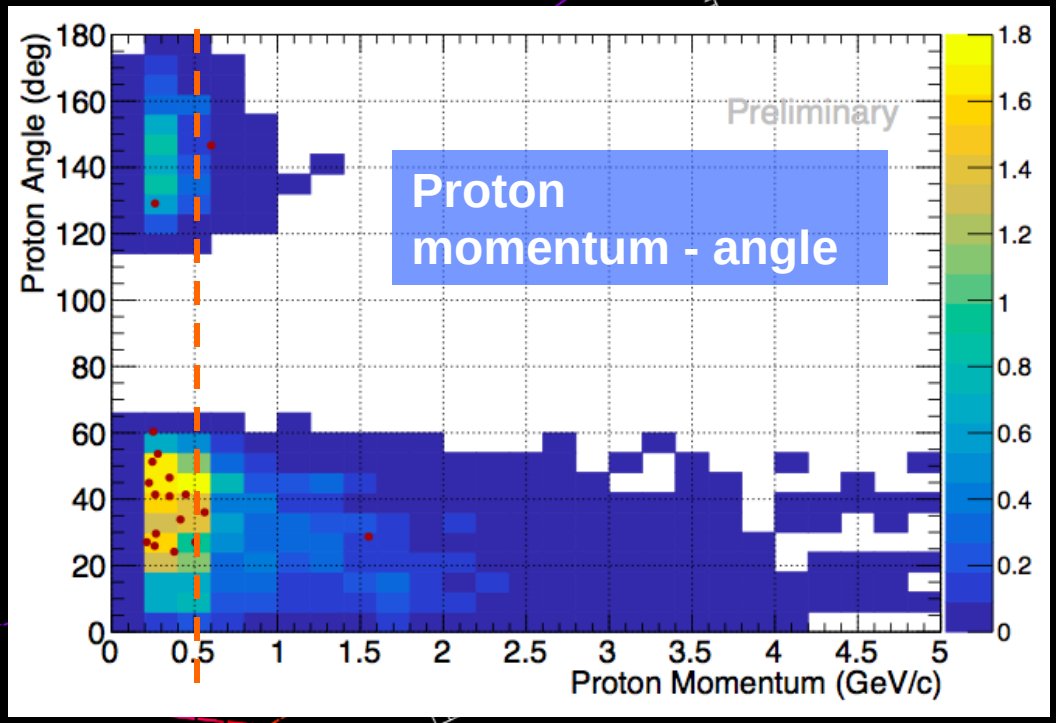
$\bar{\nu}$-water interactions



Proton multiplicity



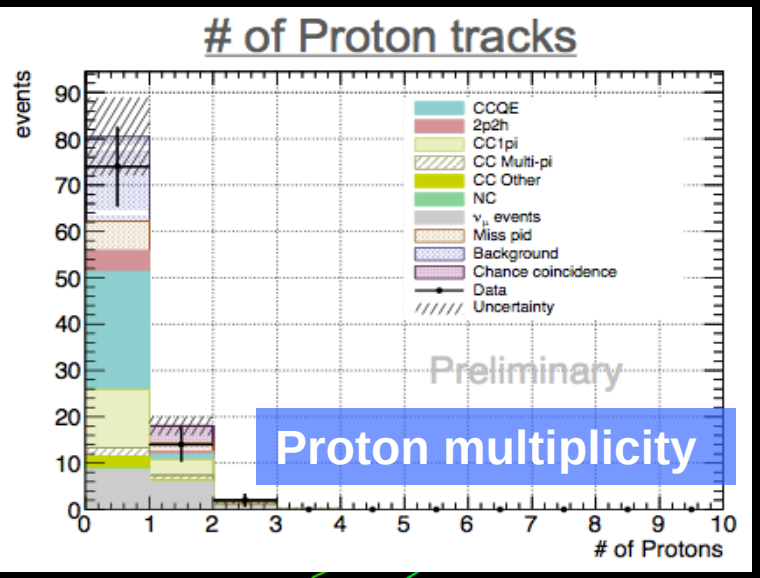
Pion multiplicity



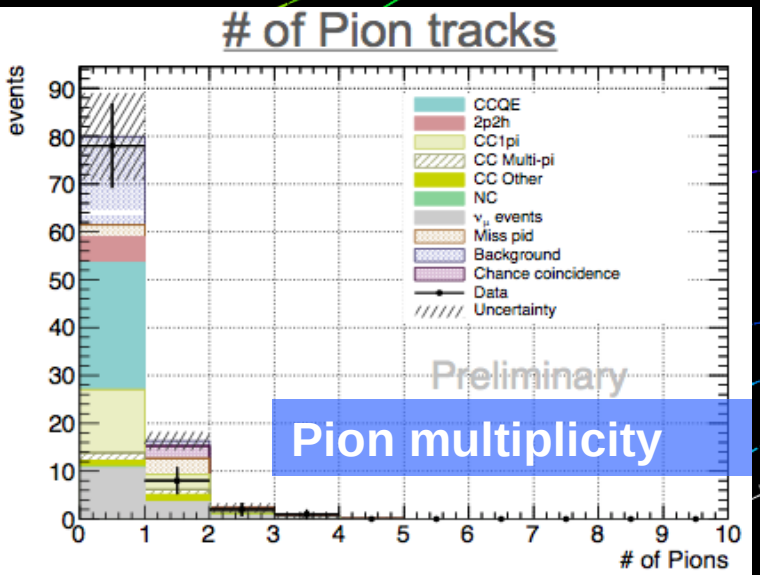
First measurement of low energy protons below 500MeV/c from $\bar{\nu}$–water interactions

NINJA

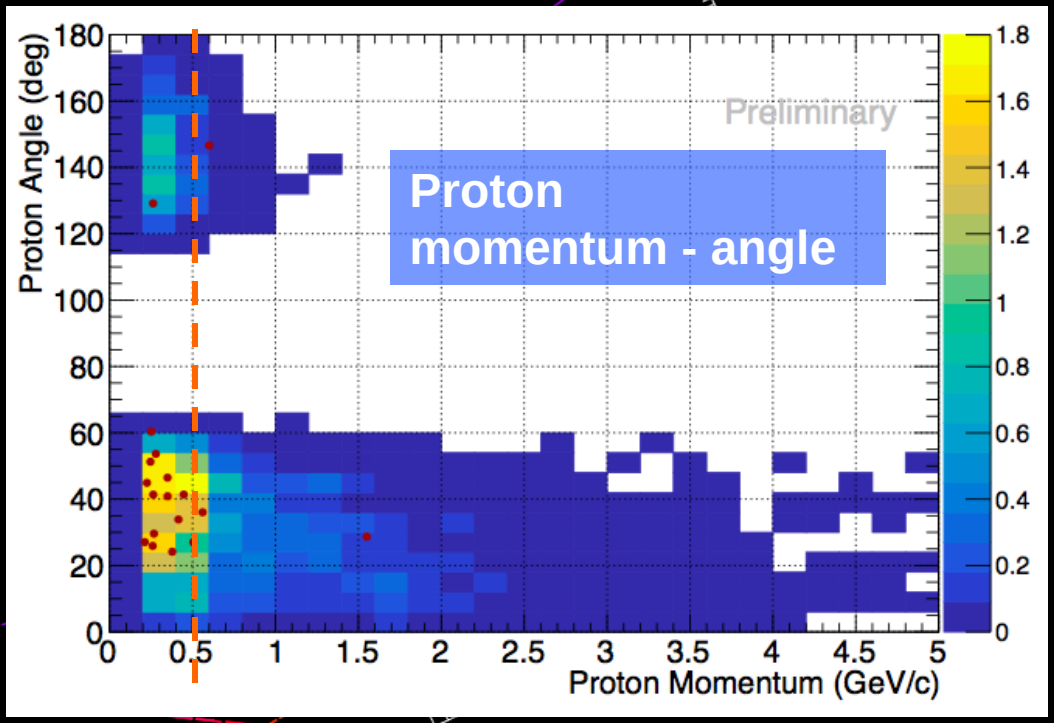
$\bar{\nu}$-water interactions



Proton multiplicity



Pion multiplicity



First measurement of low energy protons below 500MeV/c from $\bar{\nu}$–water interactions

More statistics !

NINJA

Physics Run (J-PARC E71)

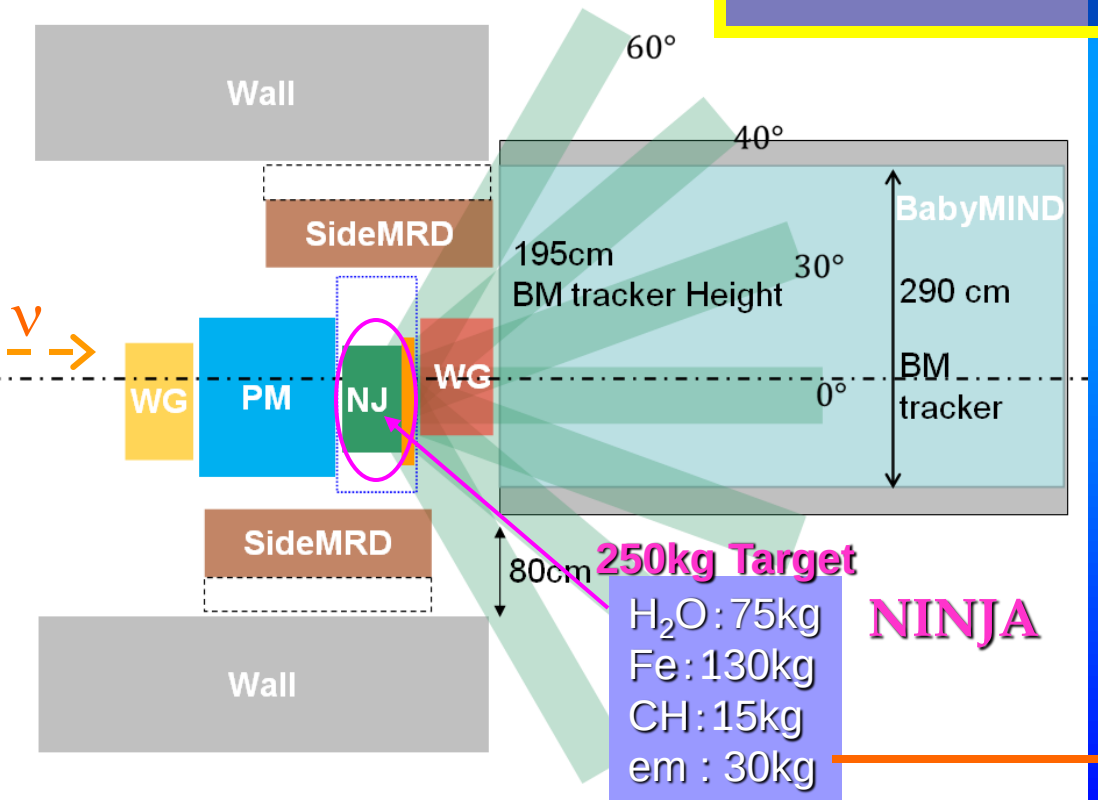
We proposed a new experiment (Physics Run) to study neutrino-nucleus interactions with large statistics.

x30 statistics

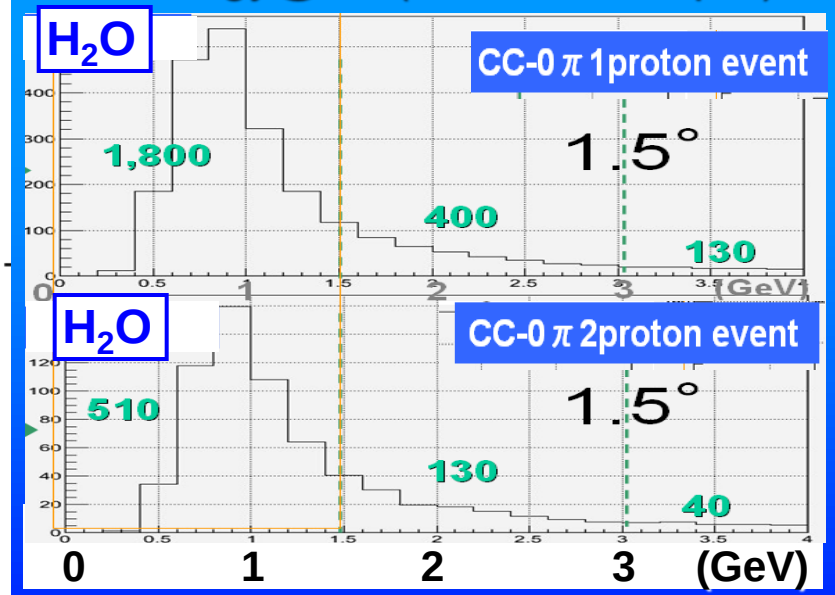
Detector setup @J-PARC B2 floor

Sub-Multi GeV Neutrino interaction

- Confirmation and cross-section measurement of 2p2h
- Exclusive cross-section measurement of ν_μ and ν_e

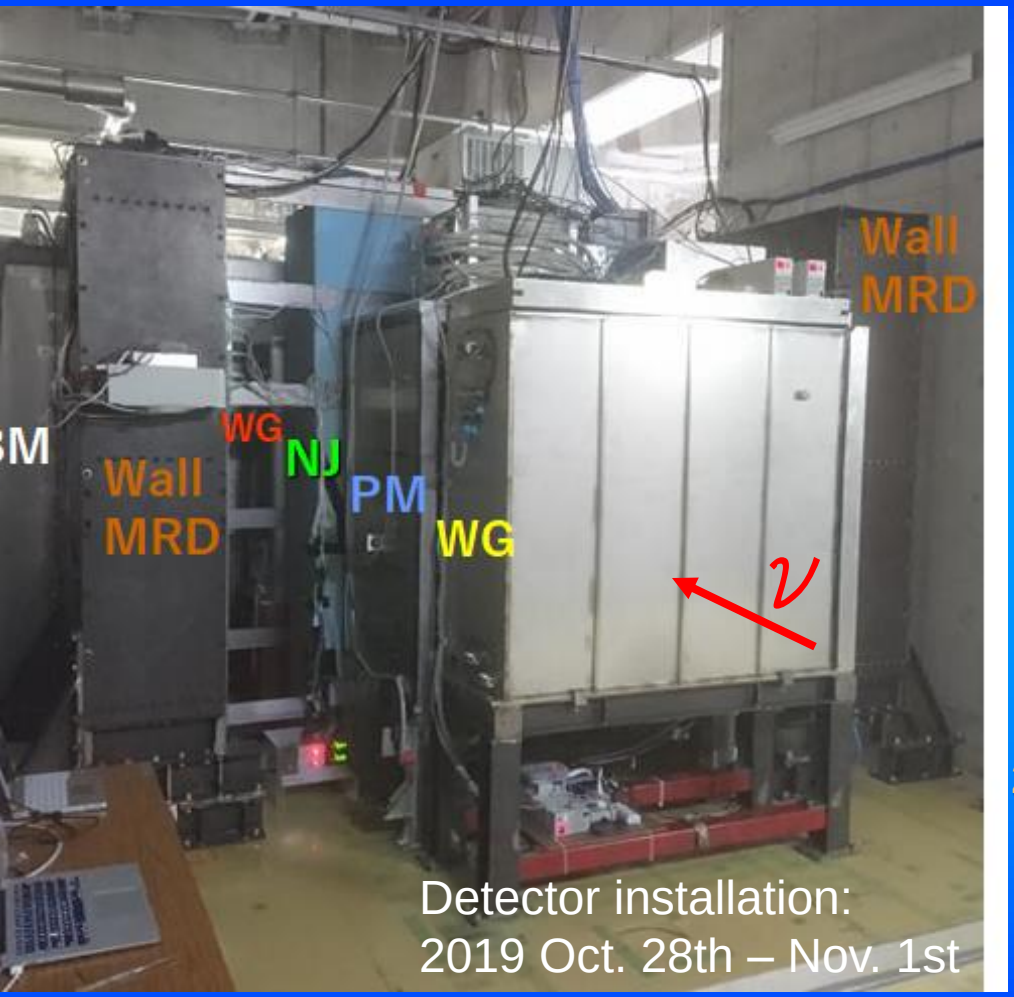


ν energy@B2 (total 1.0×10^{21}pot)

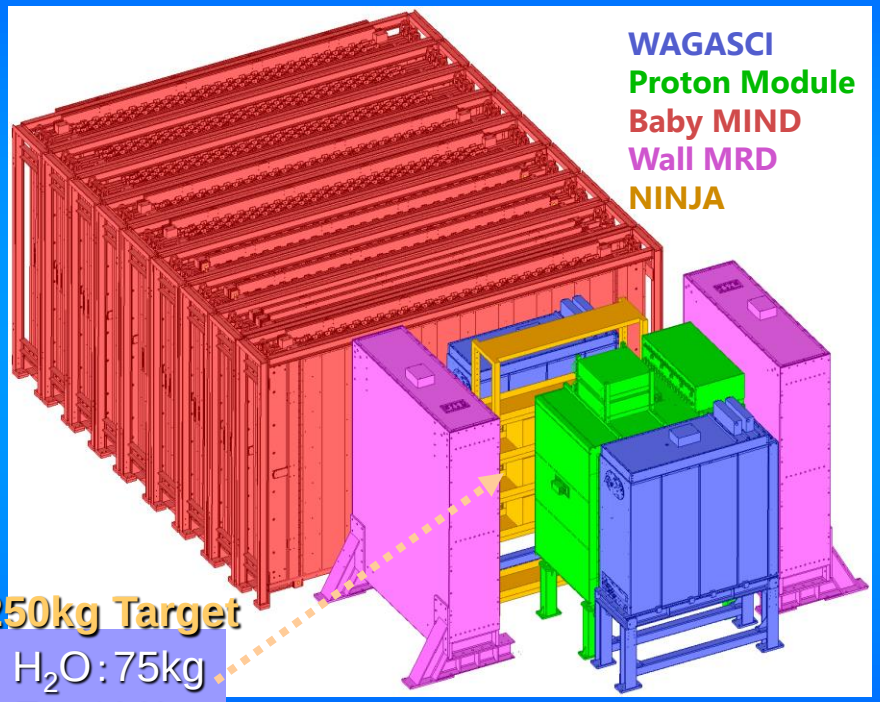


Total ~10k CC events

Neutrino detector



Hybrid with T2K near detectors
Baby MIND is used for muon ID

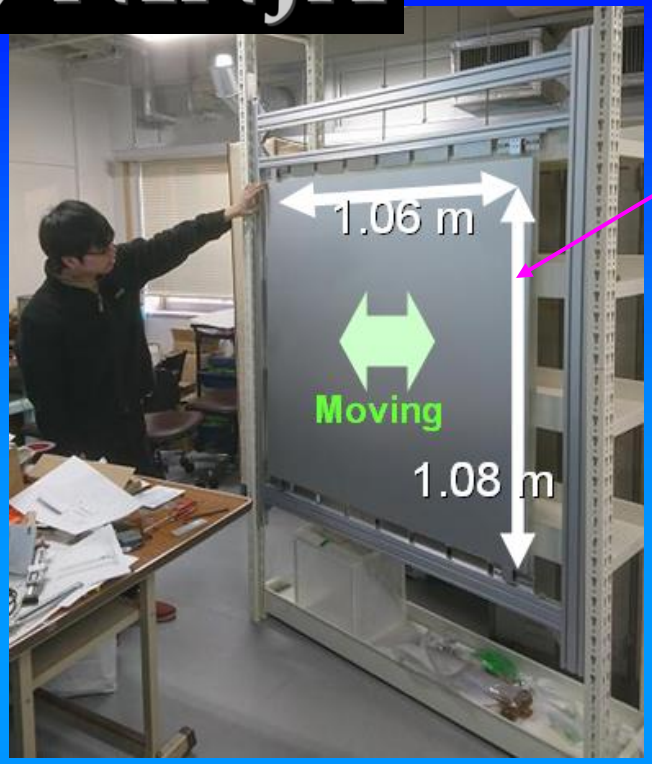


Neutrino beam: **2019/11/7→12/19, 2020/1/14→2/12**

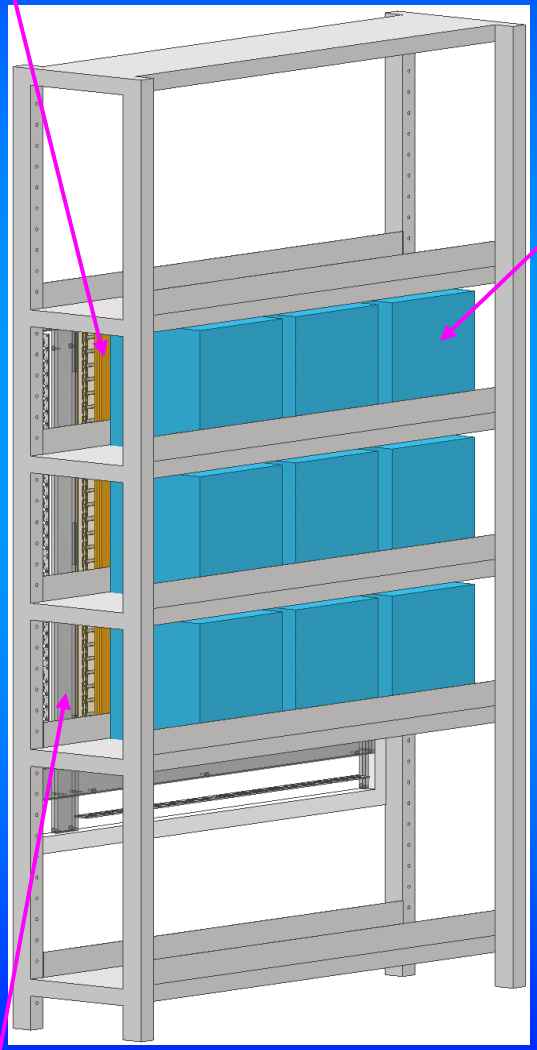
Total POT: 4.8 x 10^{20}

NINJA

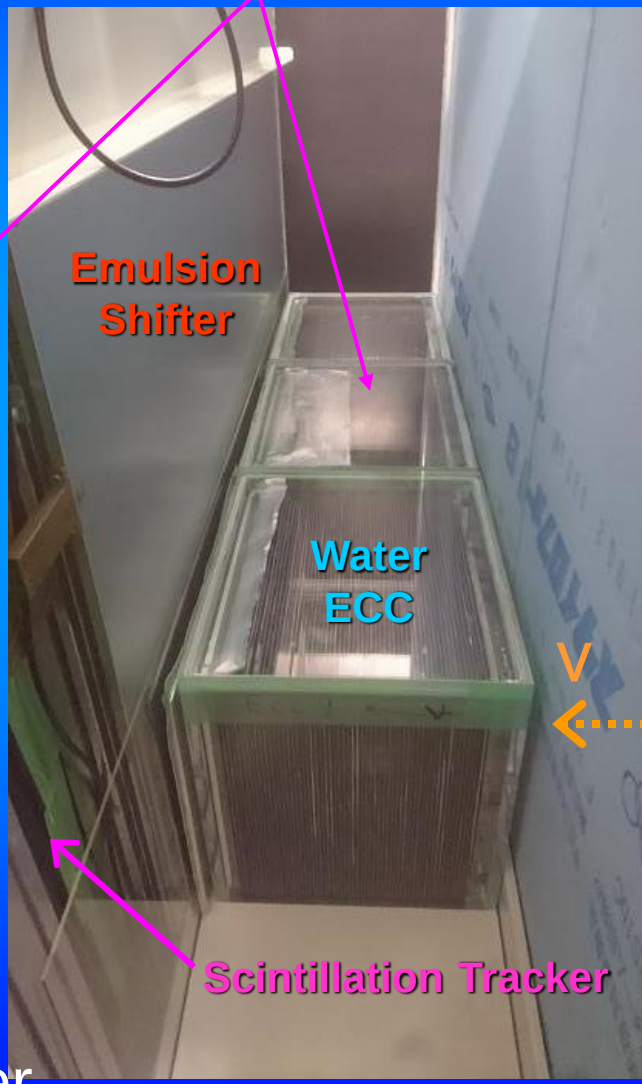
NINJA detector

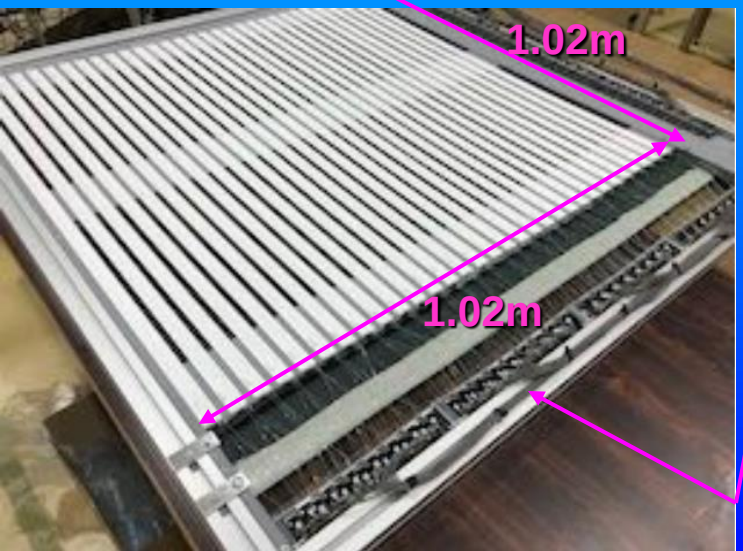


Emulsion Shifter



Water ECC

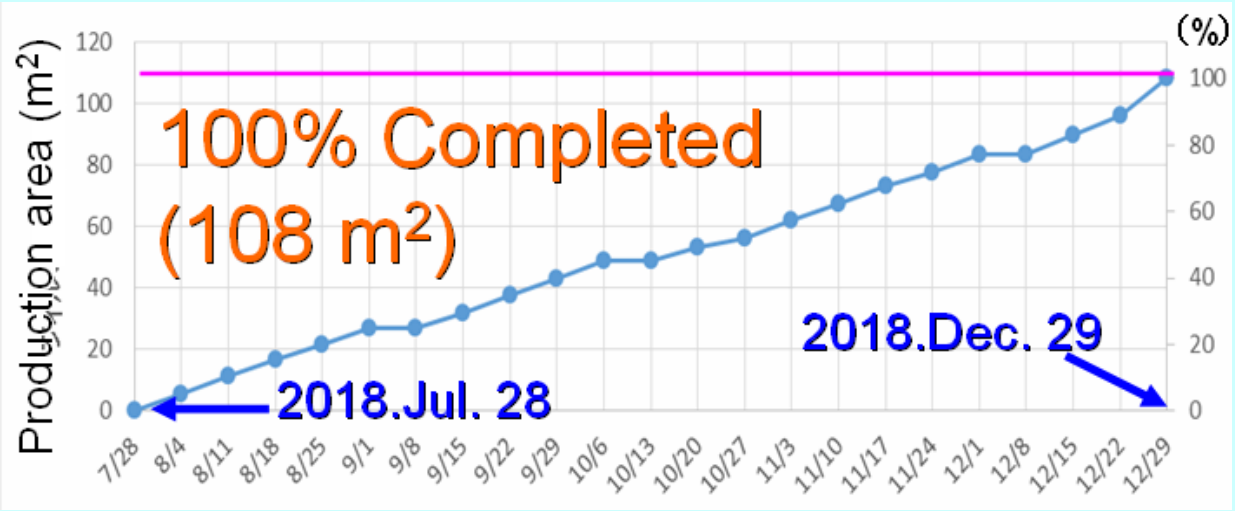




Scintillation Tracker

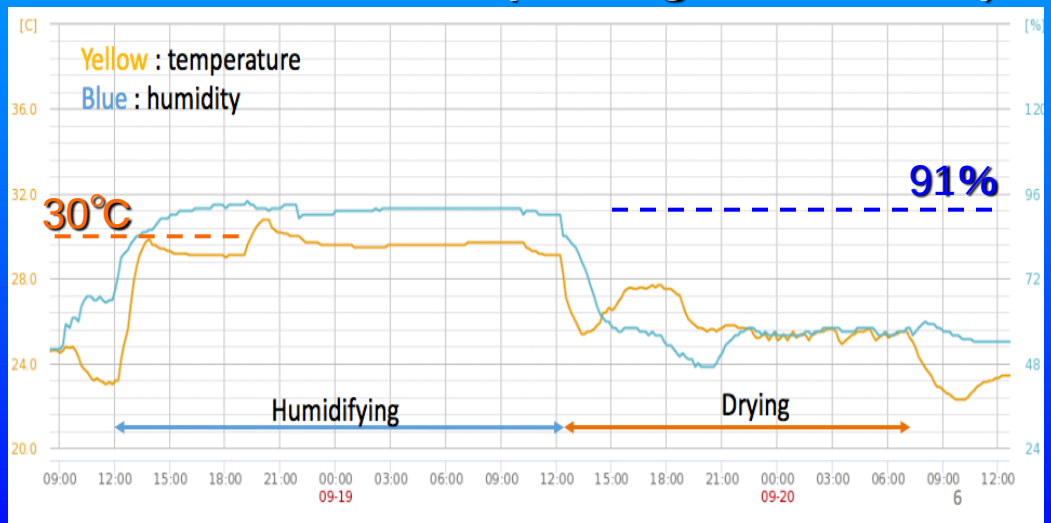
Emulsion film preparation

Emulsion film production

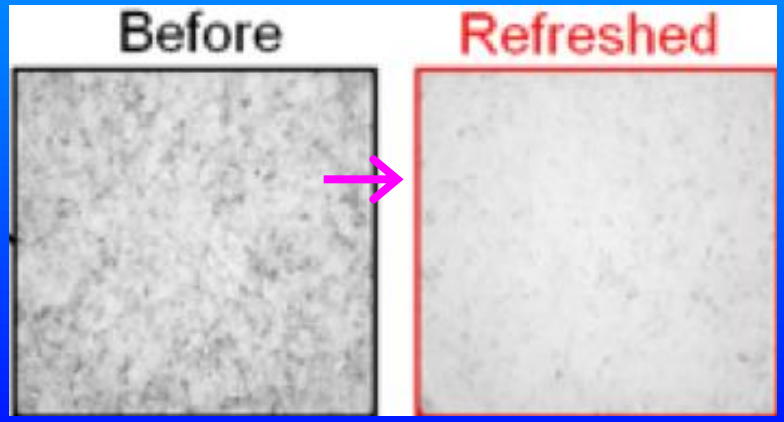


25cm x 25cm films: ~1300 films
34cm x 102cm films : ~ 25 films
~42grains/100μm → 99% tracking eff.

Emulsion film refresh (erasing noise tracks)

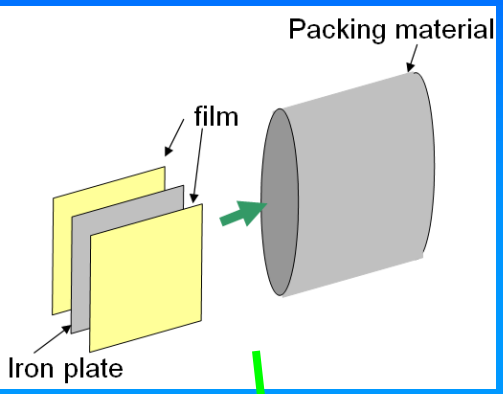


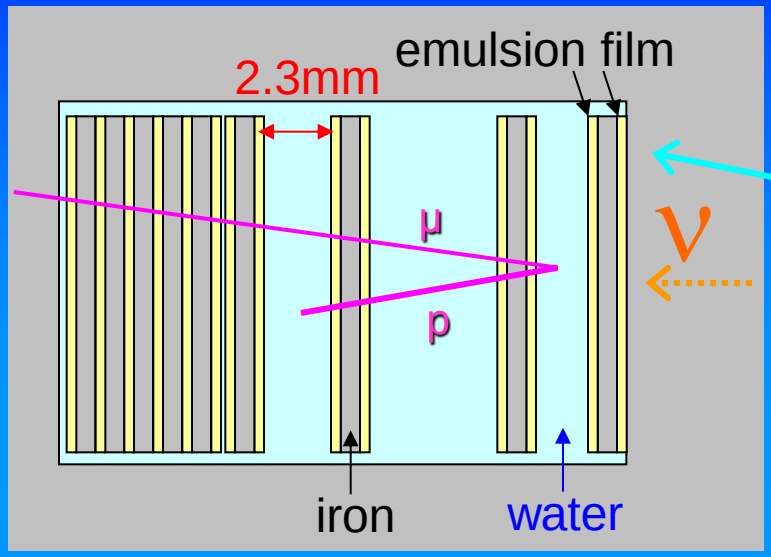
$$(Ag_4 + 2H_2O + O_2 \rightarrow 4Ag^+ + 4OH^-)$$

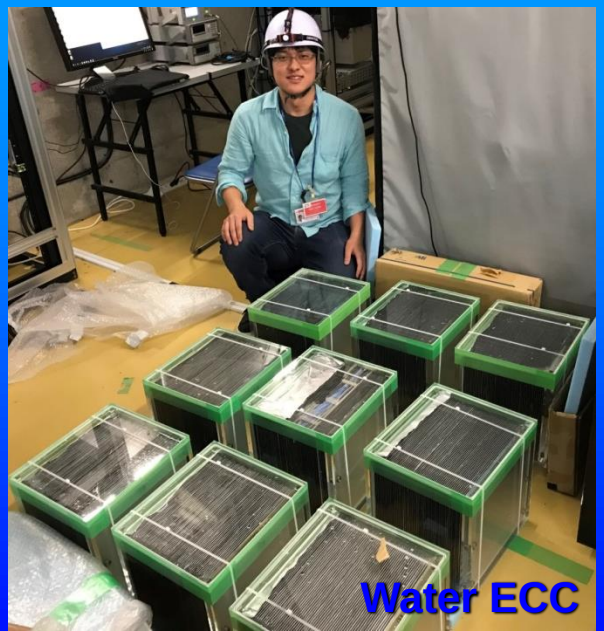


Water ECC

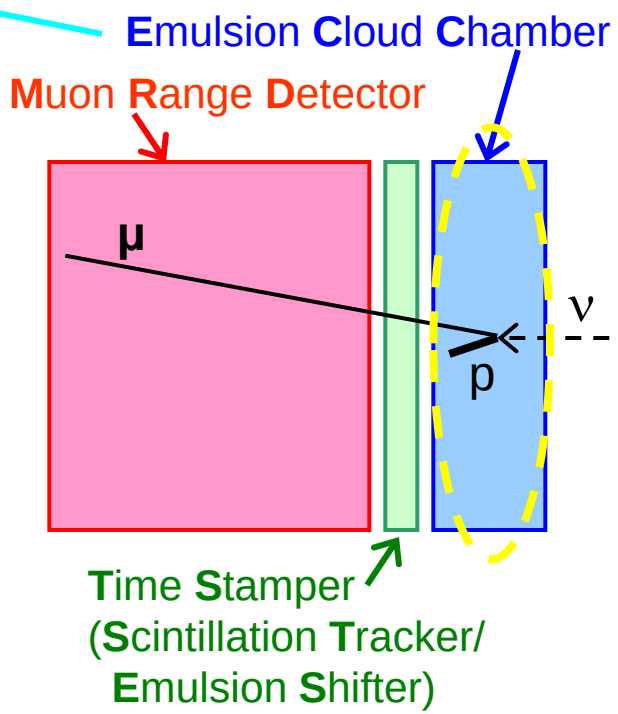
Vacuum packing in dark room





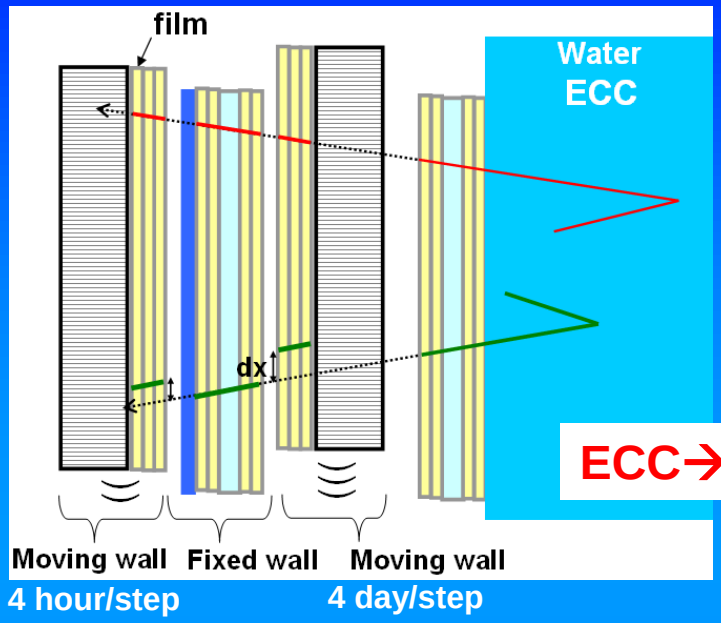


Conceptual design



ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

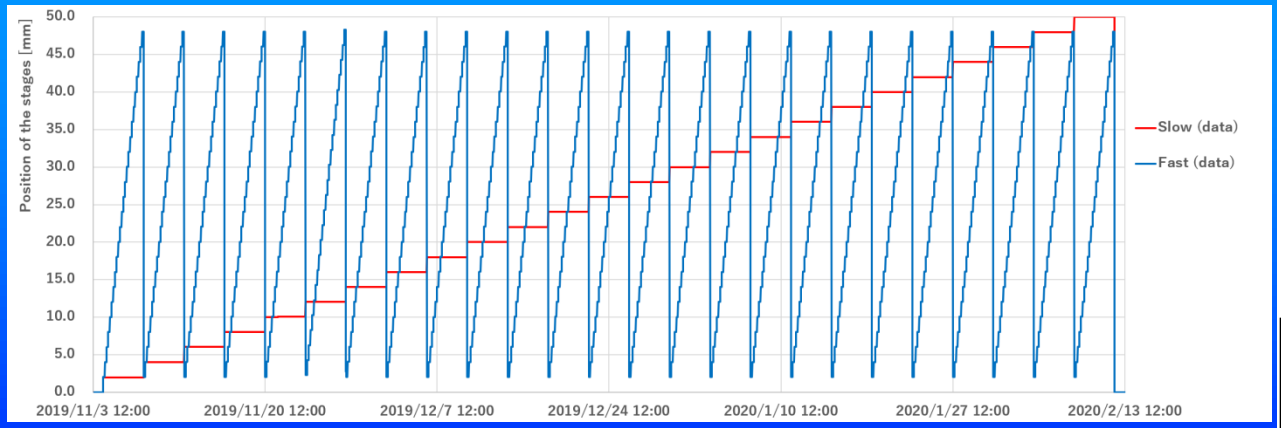
Emulsion Shifter



Emulsion films are set on moving walls controlled by stepping motor.
Time stamp is given by coincidence of each stages.

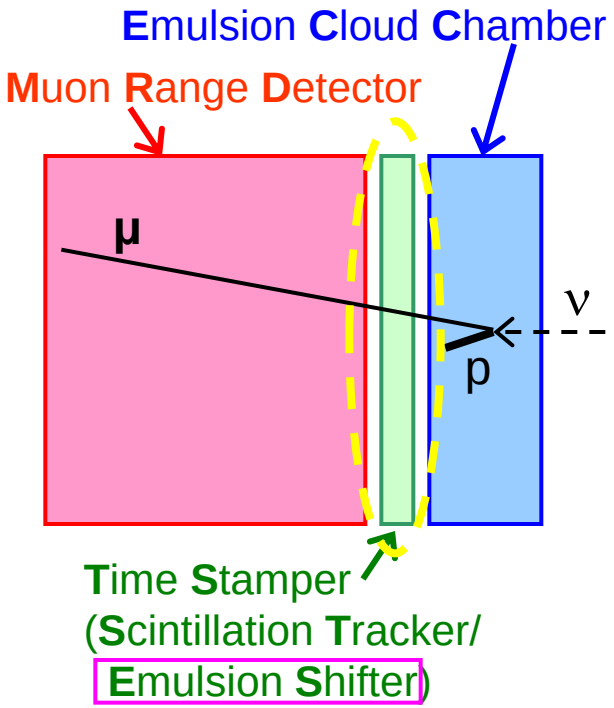
Slow wall: 4days/step
Fast wall : 4hours/step

ECC→ES: 4hour time stamp



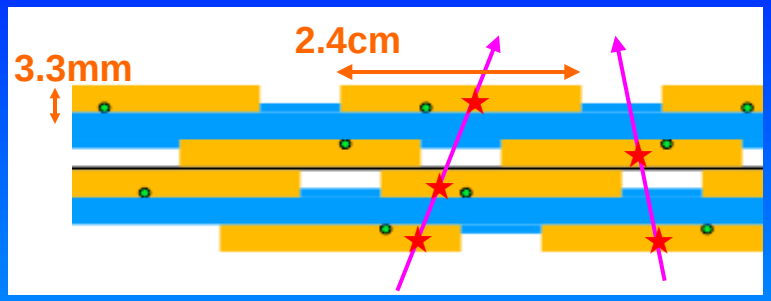
Operation of emulsion shifter was well during exposure

Conceptual design

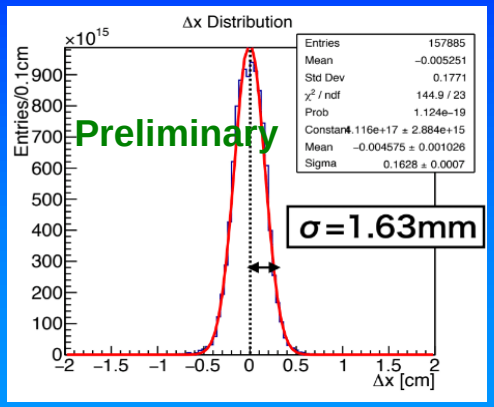


ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

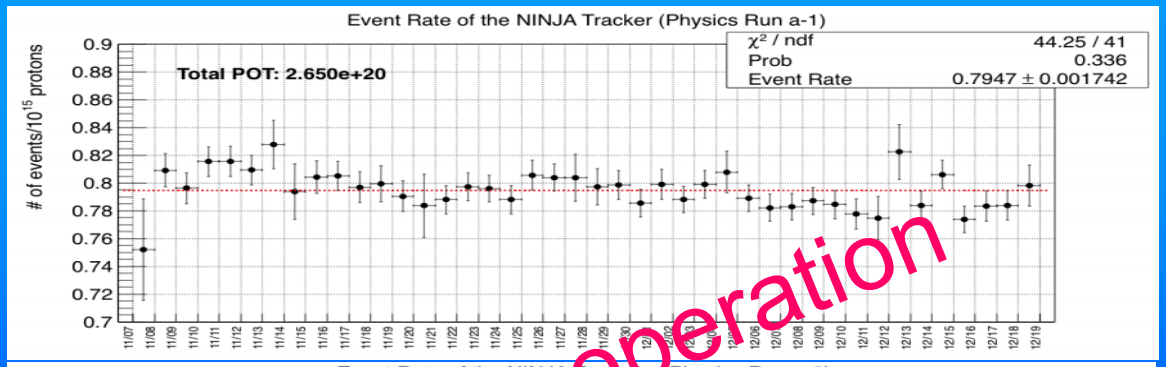
Scintillation Tracker

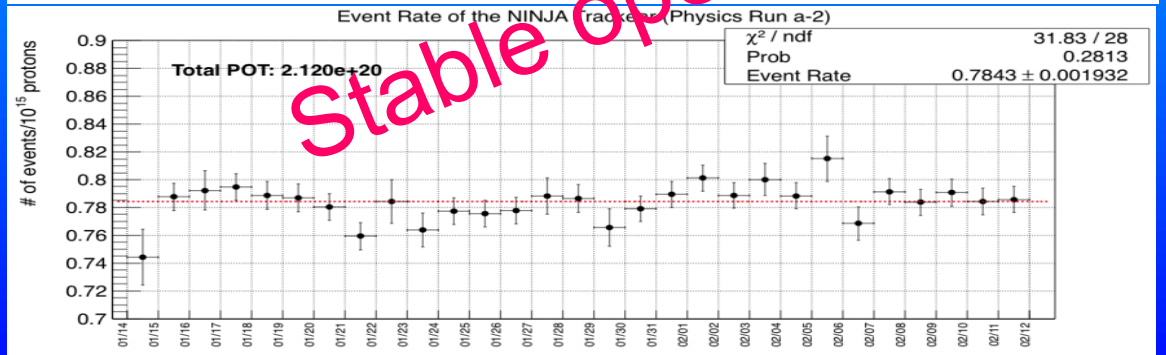


Position resolution is improved by using hit/unhit combination.
→ ~1.7mm position resolution



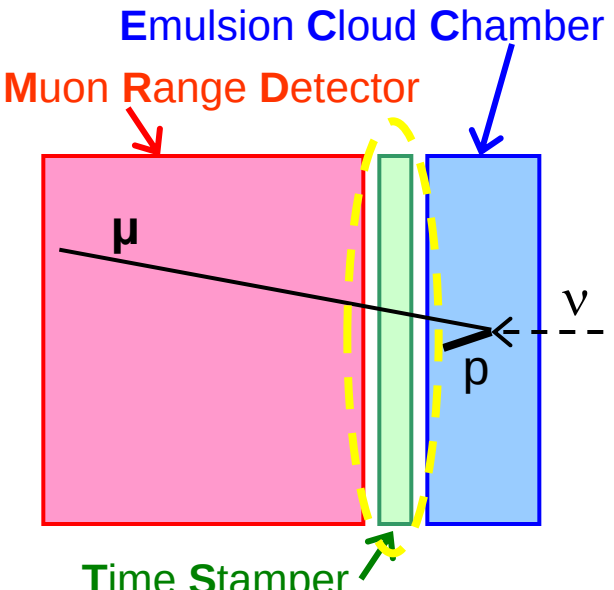
ES→ST: 10 nsec level time stamp





Stable operation

Conceptual design



ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

Baby MIND

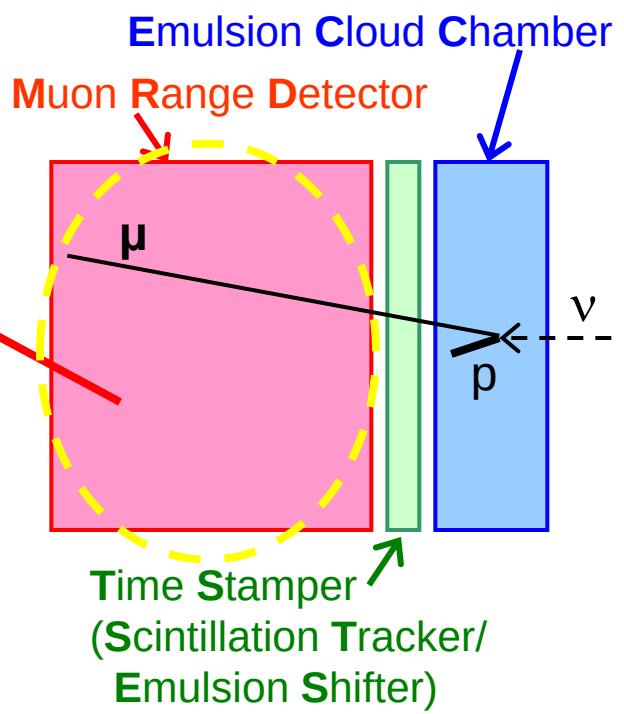
MRD for T2K-WAGASCI project
- 33 Magnet Modules (1.5T)
- 18 Detector Modules

Detection efficiency >97%
Charge identification eff > 90%
Momentum resolusion~10%

→ NINJA-WAGASCI hybrid plan
We (NINJA) can use Baby MIND for MRD.

μ^+/μ^- separation → $\bar{\nu}_\mu / \nu_\mu$ separation

Conceptual design



ECC→ event analysis
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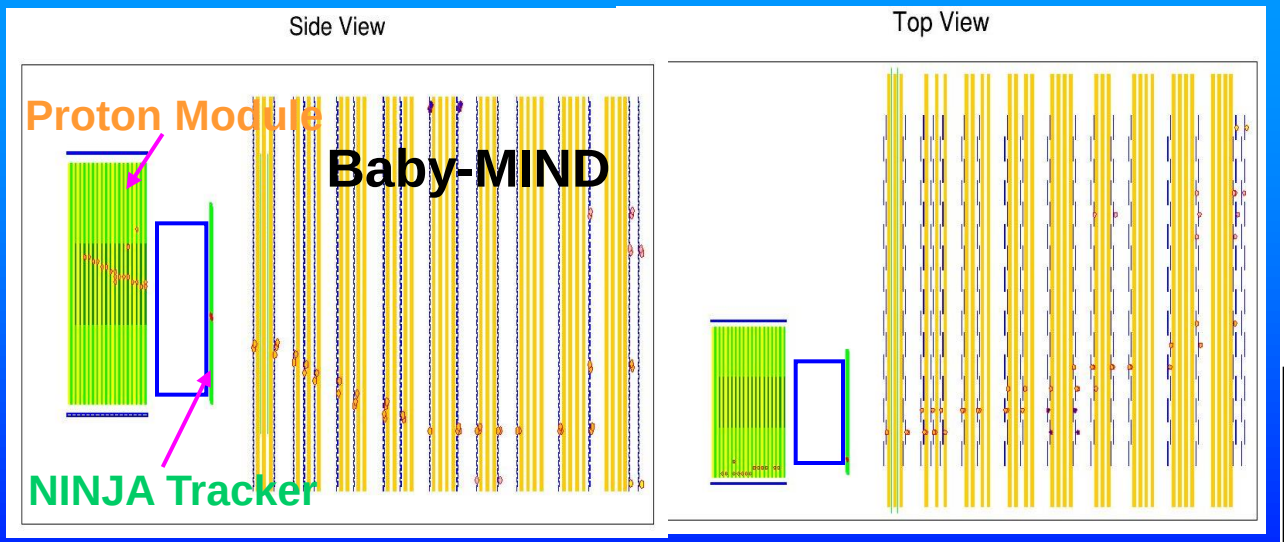
TS → event connection between ECC and MRD



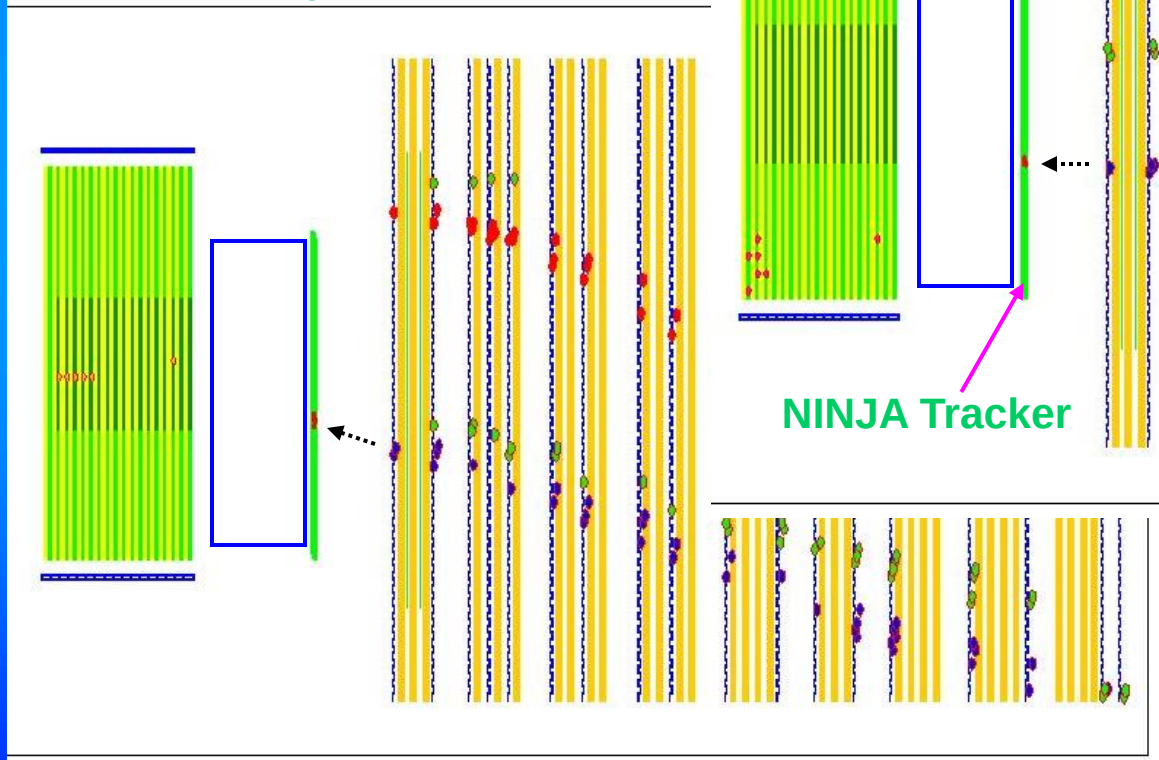
Sand muon events

Neutrino candidate events in NINJA

- No Track in PM.
- Hit at NINJA Tracker
- Track in BM

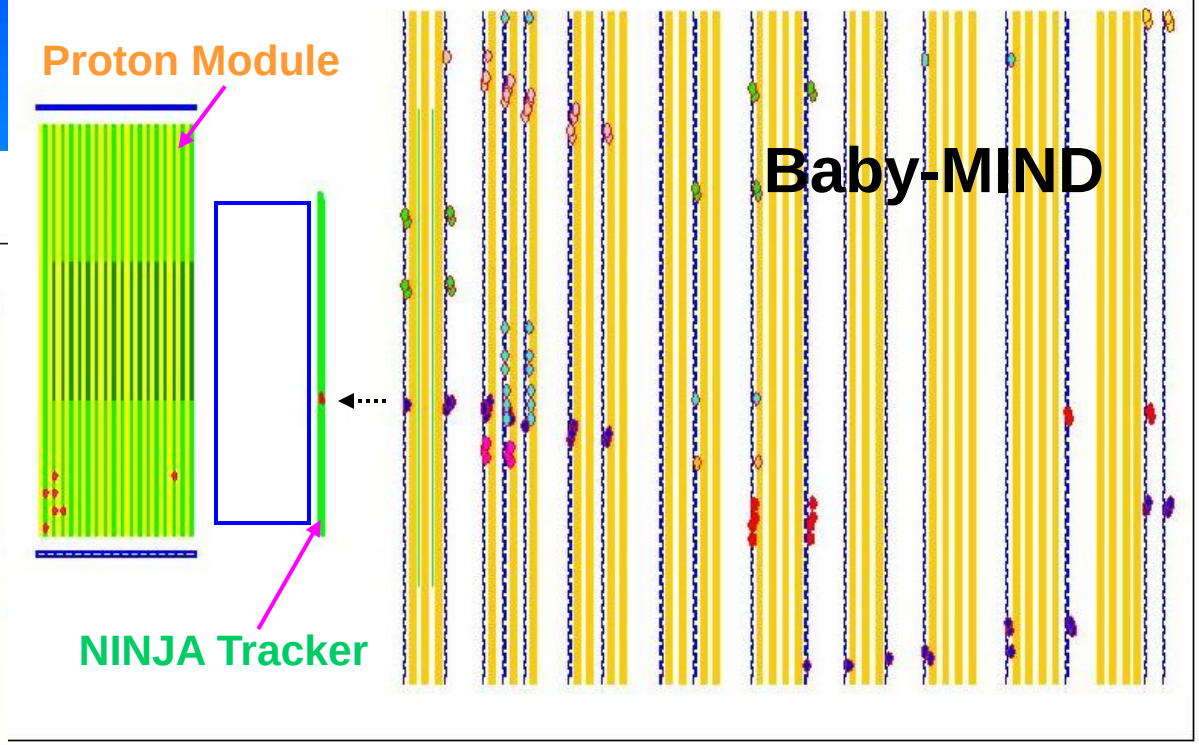
Preliminary

Side View



Preliminary

Side View



Blue color hit in BM is same bunch of NINJA Tracker hit.
(Color in NJ is only red)
(Color in PM, BM is shown as each bunch in a spill.)

Emulsion analysis will be started soon.

Expected outcomes

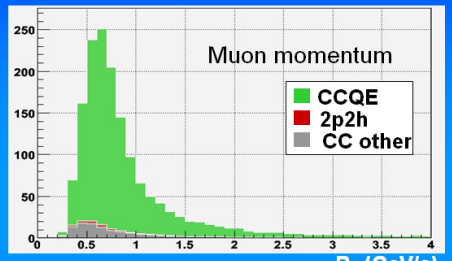
Analysis :

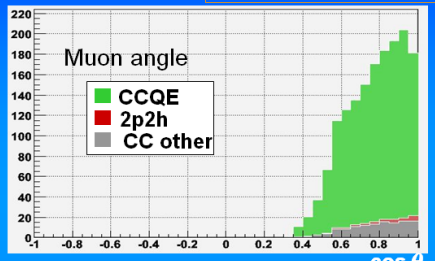
Momentum measurement :
Range,Multiple Coulomb Scattering in ECC
Range in Baby MIND (only for μ)
dE/dx measurement :
Blackness of tracks in ECC
μID : Baby MIND

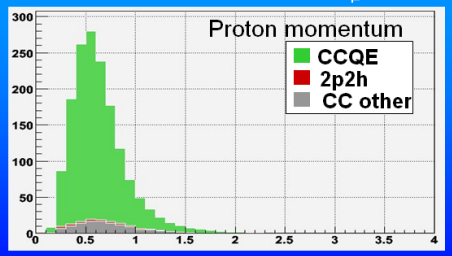
→ (Double) differential cross section measurement

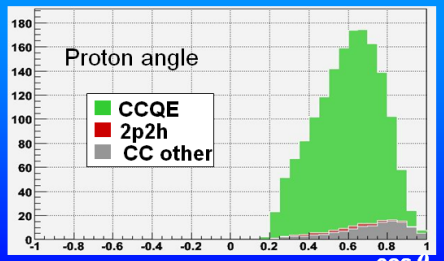
CC 0π1p event (CCQE enriched events)

Number of events (68kg water target, 1.0x10^{21}pot)
Already applied μ angle and proton detection threshold
OA＞60° , CA＞150°



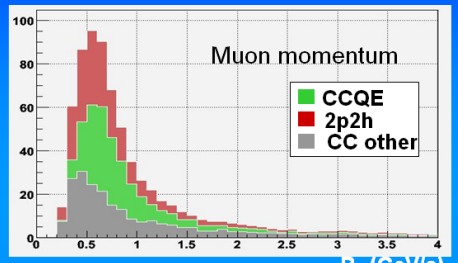


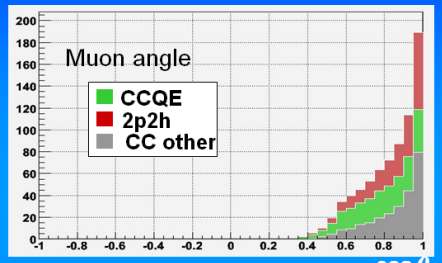


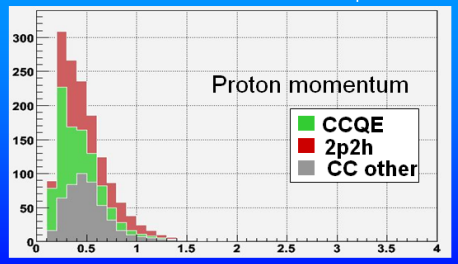


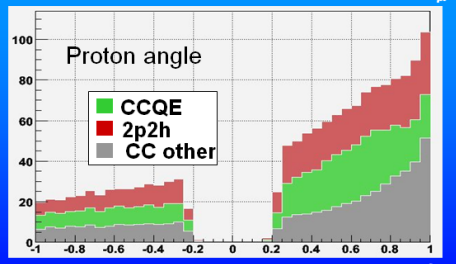
CC 0π2p event (2p2h enriched events)

Number of events (68kg water target, 1.0x10^{21}pot)
Already applied μ angle acceptance and proton detection threshold

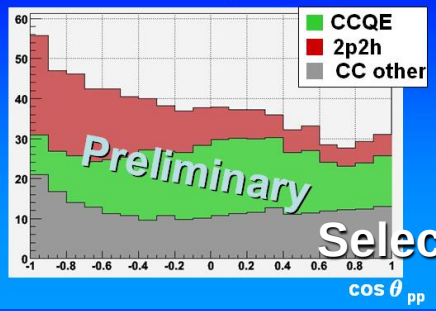








Proton-Proton opening angle



Selection will be optimized

Not only proton but also pion will be measured with low energy threshold.

Schedule (E71)

Totally >1.0x10^{21} pot @ 2 times exposure (E71a, b)

E71a (0.48x10^{21} pot) ← Our first Physics Run

2020: Emulsion film scanning
Time stamping
Inclusive measurement

2021: Emulsion film scanning
Time stamping
Exclusive measurement
(CCQE, 2p2h, 1π)

2022: ν_e measurement
Event summarizing

E71b will be started from 2022 after J-PARC accelerator upgrade
(>0.5 x 10^{21} pot)

Summary

- Precise neutrino-water interactions is important for future neutrino oscillation analysis. (especially, **2p2h** and ν_e)
- We are performing a neutrino experiments at J-PARC to study low energy neutrino - nucleus interactions by introducing nuclear emulsion (**NINJA Experiment**).
- Neutrino beam exposure for our first Physics Run (E71a) was completed in the middle of this Feb.
- We also plan to implement second Physics Run (E71b).
- We will start emulsion analysis soon.
- Discussion about contribution with nuclear emulsion for future neutrino physics is very welcome for us.